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EXPOSURES

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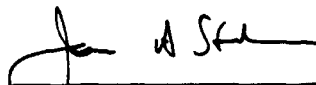
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# 1. Introduction

The well being of the soldier, which has always been the primary concern of the U.S. Army Medical Research & Development Command, is rapidly becoming a concern of the entire Army. The development of new, high-power weapons and the need to establish safe training practices has revealed the importance of the nonauditory effects of blast overpressure. In addition, blast injury is an important component of battlefield trauma. In the future, as the size of the fighting force decreases and the sophistication of the weaponry increases, the performance and effectiveness of the individual soldier becomes increasingly important. Both of these trends underscore the need for a rational basis for making health hazards assessment and performance estimation.

## 1.1 Critical Issues

In the course of training, the soldier is exposed to a variety of blast sources (small and large calibre), in a variety of surroundings (in the open and inside enclosures), and for single and multiple rounds. The Surgeon General of the Army must set conditions that limit the exposure of troops to blast overpressure (or "weapon noise") that will result in only a very small incidence of deleterious effects in the soldier population.

Military Standard 1474C [1] provides rules for determining exposure limits based on auditory hazard. The data used to formulate these limits came from small calibre (high frequency) fire. The Standard assumes that the blast field can be characterized by two parameters: the peak pressure and a time duration. Based on those two quantities, a maximum number of exposures is determined. If the combination of quantities exceeds the "Z-line," the Standard allows no exposures because of unspecified "nonauditory" danger.

When an exposure exceeds the Standard's nonauditory limits, man-rating studies must be conducted to establish exposure limits on a weapon-by-weapon basis. This is a time-consuming and expensive procedure that is likely to become more and more common as weapon power increases. Furthermore, when the blast overpressure hazard arises in an enclosure, the variation and permutations of the exposure become so enormous that case-by-case studies are not feasible.

When blast overpressure levels increase further, the concern switches from identifying threshold to anticipating soldier performance and effectiveness. Here, the guidance for Army doctrine has come from animal tests, largely concerned with lethality estimates. More recent animal tests and more thorough analysis of previous test data reveals that physiological effects are present at much lower values than had been previously thought and involve all of the body's air-containing organs.

Finally, animal studies that consider the effects of combined trauma have shown that the pathophysiological consequences can be profound, and could have implications both for the individual and for the medical care system. Once again, the elements entering such estimates do not properly reflect what is known about the physiological consequences of blast overpressure, nor is enough known to be able to confidently anticipate the consequences.

## **1.2 What Has Been Done**

During the past decade, the US Army Medical Research & Development Command (USAMRDC) has sponsored programs to establish more general risk criteria for weapon noise hazard. The goal of these programs is to relate the hazard to general features of the pressure signal so that case-by-case studies will not have to be conducted. Four different approaches are being followed.

1. Human volunteer studies at the Albuquerque BOP Test Site, under the direction of the US Army Aeromedical Research Laboratory (USAARL), have been conducted to determine the threshold of temporary auditory effects for soldiers exposed to simple, free-field blast waves. Even with the lowest level of hearing protection, the study indicates that there are no auditory effects below the Z-line.
2. Animal studies are being conducted at the Albuquerque BOP Test Site, under the direction of the Walter Reed Army Institute of Research (WRAIR), to determine the threshold injury levels to the upper respiratory tract (URT), which has been assumed to be the most susceptible organ. That data, when plotted on a peak pressure-duration graph, has been used to establish an empirical nonauditory threshold that may replace the nonspecific Z-line. Other animal tests are providing the first information on injury in complex wave environments.
3. Mathematical models of the biomechanical response to blast are being developed at JAYCOR, under the direction of WRAIR. For certain choices of the mechanical and biological properties of the organ, URT and lung damage can be correlated with models of cumulative, mechanical damage.
4. Physiological measurements of animals exposed to blast overpressure are being conducted at WRAIR. These studies will characterize the long-term biological response by measuring a wide variety physiological, biophysical, and biochemical quantities. Results reported so far indicate that blast exposure, when combined with exercise, produces effects that are more extensive than previously thought and may involve cardiac as well as pulmonary effects.

The findings of these various efforts relevant to developing a generalized Health Hazard Assessment methodology can be summarized as follows.

1. Safe exposure to free-field blast overpressure, when a minimum of hearing protection is provided, is determined by nonauditory hazard.

2. All target organs (URT, lung, and gastrointestinal tract) have comparable thresholds of injury and that threshold is lower than had been previously estimated.
3. Hazard in a complex wave environment occurs at overpressure levels smaller than in the free-field and a larger fraction of the affected organ is damaged. Even the description of the wave field cannot be reduced to a small set of parameters.
4. Biomechanical modeling can provide a rational explanation of empirical damage observations that could extrapolate current results to new conditions.

### **1.3 Shortcomings of the Current Standard**

The current Military Standard offers only limited guidance for setting exposure conditions for many cases of interest to the Army. There is no way of handling complex blast waves, mixtures of different blast types, or combinations of auditory and nonauditory hazard. The estimates of performance and physiological consequences are not addressed at all.

The correlations used by the Army for estimating performance and combat effectiveness are now known to overestimate the levels at which effects appear and underestimate the severity of the response. Effects of subsequent activity, such as exertion, and the effects of combined or additional trauma are believed to be significant but have not been quantified systematically.

### **1.4 What is Needed**

To be able to make a rational, reliable Health Hazards Assessment, a single, self-consistent means for determining the biological and performance consequences to the soldier population from combinations of blast exposures is needed.

The methodology must:

1. Deal with objective measures of the blast environment (measured pressure-time histories), not with simplifications (such as peak pressure and duration).
2. Provide a means of guiding the placement of blast instrumentation, checking credibility of the data, and extrapolating the results to other locations.
3. Put hazard from auditory and nonauditory effects on a common basis so that a total hazard can be determined.
4. Determine effects in the population as well as the individual.
5. Be validated against known data.
6. Be unambiguous and useable by all parties.
7. Be applicable to free-field and complex waves.
8. Define physiological as well as pathological consequences of blast.

A collection of mathematical models, calibrated and validated by the experimental data, can meet all of these requirements.

## 1.5 Relevant JAYCOR Experience

JAYCOR has been conducting research for the USAMRDC for the past ten years on the application of engineering techniques to the understanding of the biomechanical consequences of blast. Most of the effort has been directed toward the lung and the gastrointestinal tract, however, there are aspects of our work that directly bears on the health hazard assessment.

**Free-field Blast Prediction.** Our first contract for the USAMRDC included a task to use gas dynamics simulations to determine the significant features in the pressure time histories collected around the M198 howitzer. We developed a blast propagation model (BLAST) for the far-field that agreed very well with the measured data. With this model we could confirm the correctness of the observed traces, eliminate features that were "noise," and provide an extrapolation of the results to any position around the weapon.

Now that the weakness of a two parameter description of blast in the free-field is known, the BLAST model will be important to making free-field health hazard assessments.

**Complex Blast Prediction.** JAYCOR specializes in Computational Fluid Dynamics (CFD), the calculational techniques that are widely used in engineering to simulate complex fluid problems by solving the fundamental governing equations with numerical algorithms. Over the past 15 years we have developed a proprietary program, EITACC, that can simulate explosion dynamics from the chemical reactions that generate the blast, through the propagation of the wave, interaction with solid walls or openings. The simulations offer the ability to study a complex situation in great detail before conducting field tests or before exposing man or animals.

Often, a more approximate estimate of the blast field is sufficient and greater simplifications to the mathematical description of the phenomena can be made. The BWAVES code makes such a simplification by assuming that the blast waves reflect from the walls like perfect mirrors. Borrowing a concept from geometric optics, the method of images can provide a simulation, that runs on a desktop computer, of weak blast waves in an enclosure.

**Mechanistic Models of Biomechanical Response.** As part of contract DAMD 15-85-C-5238, we developed a single degree of freedom model of the biomechanical response of the trachea to blast. Using somewhat arbitrary parameters, that model was able to correlate URT injury with the stress level in the trachea. Since then, we have explored the use of Finite Element Modeling (FEM) to provide better mechanical properties and have discovered experimental data on tissue strength that will provide better damage correlates. Both of these aspects will be important to the nonauditory component of health hazard assessment.

In that same contract, we developed a FEM model of the tympanic membrane that shed light on the mechanisms and patterns of ear drum rupture [2]. We use the FEM results to construct a single degree of freedom model that could correlate rupture in cadaver specimens with maximum membrane stress. Even though this model is incomplete at this time (the effects of the outer ear and ear canal are not taken into account), insight into tympanic and auditory hazard might be obtained.

**Cumulative Damage Concepts.** It is well known that the threshold of injury decreases with repeated exposures. Using an analogy based on the fatigue of materials, we developed a cumulative damage concept for biological systems. The concept assumes that subcritical damage is done with each exposure and accumulates logarithmically, as is seen in non-biological materials. The concept has proven promising in correlating multiple exposure data for the URT.

**Threshold Injury Levels.** After we had developed our first biomechanical model of the lung, we found that the animal data to validate it had not been compiled into a useful form. Consequently, most of contract DAMD17-89-C-9150 has been concerned with the organization, qualification, and analysis of all of the free-field data taken at the Albuquerque BOP Test Site over the past ten years. As a result, we can now determine injury thresholds with a high degree of accuracy and confidence. In particular, that work has revealed that the threshold injury levels for the URT, lung, and gastrointestinal tract are nearly the same and lower than the value estimated earlier from lethality studies.

**Incidence of Injury.** Another analysis made of the pathology database determined the incidence of injury in the animal population. That analysis forms the basis for the dose-incidence relations needed in health hazard assessment.

**Incidence of Multiple Effects.** Once the dose-response and dose-incidence relations are known for the auditory and nonauditory effects, they must be combined into a single hazard model that can be used to make trade off decisions. The need for defining the incidence due to multiple causes arose in our work on combined injury on the nuclear battlefield [3]. There we developed the mathematics of combined injury that can be directly applied to this problem.

## 1.6 Goals of the Current Work

The work planned will meet the needs identified above in a timely and cost-effective means. The work builds upon the research conducted by JAYCOR for the USAMRDC over the past decade and upon JAYCOR's special engineering skills in blast dynamics. The objectives of the work are described below.

1. Extend the pathological database so that all physical and pathological data from all blast exposure tests can be entered, queried, and analyzed.
2. Develop a single methodology that provides a means of estimating:
  - a. Threshold injury from free-field and complex waves
  - b. Severity of lung injury
3. Develop a methodology to estimate total hazard from auditory and nonauditory effects.
4. Deliver a user-oriented, validated computer program which can be distributed in a controlled form that will guide material development and health hazard assessments.

## 1.7 Methods

All of the methods that will be employed in this work have been well documented, are in active use by JAYCOR (many of them specifically developed by JAYCOR), and represent the state of the art in biomechanical and blast overpressure modeling.

To accomplish the first objective, a single database for blast and pathology results, we will build on existing software products:

- ☐ PATHOS: a relational database for text and photographic data.
- ☐ VU: a program for storing and viewing pressure time histories.
- ☐ GDIF: a language for translating data between file formats.
- ☐ JAYPAD: a program for digitizing hardcopy pressure records.

To accomplish the second objective, a unified methodology for nonauditory effects, we will use the following software to define the blast field:

- ☐ BLAST: a program for computing blast propagation in the free-field.
- ☐ BWAVES: a program for computing complex waves using the method of images.
- ☐ EITACC: a Computational Fluid Dynamics program for general blast analysis.

use the following mathematical models of biomechanical response:

- ☐ Single Degree of Freedom (SDOF) models for the
  - Tympanic membrane
  - URT
  - Lung
- ☐ THOR: one-dimensional model of thorax-lung dynamics.
- ☐ ADINA: multi-dimensional Finite Element Model of thorax-lung dynamics.

and use the following physical model:

- ☐ Chest wall-lung surrogate dynamics model.

To accomplish the third objective, a total hazard model, we will use a collection of mathematical models and concepts:

- ☐ Auditory dynamics models (to be provided by USAARL).
- ☐ Statistical analysis methods for dose-response curve.
- ☐ Combined incidence relations.

To accomplish the fourth objective (a user-oriented assessment program) we will use:

- ☐ INJURY: a desktop computer program solving the SDOF models and related injury correlations.

## 2. Research Summary

### 2.1 Animal Test Data

Over the past 15 years, under USAMRDC sponsorship, field tests have been conducted to provide the animal data required to test and refine the mathematical models of the health hazard assessment methodology. The combined information from these tests is massive. A single test may contain megabytes of transient pressure data, hand written log records, documents, pathology reports, and images in the form of photographs, movies, or video. JAYCOR continues to process this data into computer manageable form, compact the size where possible, and deliver to the Army the data and programs to use the data. Over 120 MB of scanned photographs and 100 MB of compacted data traces have already been processed and delivered by JAYCOR along with the summarized pathological records of nearly 1000 animals. The data flow is increasing rapidly because the number of tests are growing and the amount of data collected on each test are better documented.

#### 2.1.1 New PATHOS Database

PATHOS 1.0 does not contain blast data fields, which makes it difficult to study correlations. As part of the generalization of PATHOS, we have converted all of the current pathology data to dBase format (so it can be used by software both for queries and analysis). In this step we are associating blast information with each animal. Eventually, all of the pathology and blast data for each animal will be in the same database.

**Organ Regrading.** The pathology scoring was not as complete and systematic for the free-field tests as it is now. For example, an overall lung injury score was given, but not separate scores for individual lobes. Furthermore, lesions for individual sections of the GI tract were reported, but, for some studies, not a total GI score. Occasionally, pathology scores are missing, even though necropsy diagrams and photos are available. During the last contract, we began a regrading effort to fill in the missing data and to achieve a greater uniformity over all tests. A subjective injury scoring system was proposed that closely follows the rules used by the investigators at Albuquerque. Preliminary regrading of the lung was reviewed by Dr. Dodd of WRAIR. We have now completed the regrading for all of the free-field tests.

**Free-Field Tests.** The free-field pathology data is stored in an Informix data structure that the current PATHOS accesses. To make queries (data extractions) for analysis requires modifying the PATHOS program or using the Informix language tools, both of which are cumbersome. By converting the format to dBase, the data will be accessible to the more general tools JAYCOR has developed for Windows applications and, eventually, can be accessed by products such as EXCEL. We have made the conversion of the data itself between the file formats and have established new field names.

**Bunker Tests.** All of the animals in the complex wave study tests from 1990 and 1991 have been added to the new pathology database. Since extensive photographic data is available, we have graded the pathology according to the area based system used in the free-field. This re-grading was necessary because the grading system was changed for tests subsequent to 1990 and no longer affords a direct comparison with the previous free-field results. Since a principal goal of the modeling effort is to demonstrate that biomechanical concepts can span free-field and complex blast environments, it is necessary to have a common injury measurement system to judge that comparison. It should be a goal of future project coordination to resolve these differences and standardize the pathology grading.

**Measured Pressure Data.** A new field has been added to the database for the name of the GDIF file containing a measured pressure trace. In the final HHA analysis package, that name will allow the user to retrieve the pressure plot from the database. The correct (p, t, I) measured data has been entered into the database and appropriate field names chose. Of course, this data is available only in those cases where records exist. All pressure traces from the 1990 and 1991 complex wave studies have been converted to compact GDIF format. See Figure 1.

**Computed Pressure Data.** The formulae for free-field blast parameters, derived elsewhere, have been used to produce computed values and have been stored in new fields. Because the test conditions are always known, even when the blast data wasn't reported, we now have a complete set of parameter data to be used in developing correlations.

**Photographic Images.** The current version of PATHOS incorporates scanned photographic data in a "hard wired" system of file names that does not allow easy expansion nor compact storage of selected test data. The future data management system, built around JAYCOR's IISYS system, will remove these restrictions. In order to organize the photographic data already collected and to lay the ground work for the IISYS implementation, field names have been added that identify the photographic images available.

### 2.1.2 Free-field Data Qualification

A complete and accurate description of the blast wave (pressure time history) for free-field explosions is needed as input to our biomechanical models. The data currently associated with the animal pathologies have been incomplete, incorrect, and conflict with other sources. These problems must be resolved and the findings documented so that we can concentrate on the development of the biomechanical models.

It is assumed that the free-field pressure trace can be characterized by three parameters (peak pressure, A-duration, and A-impulse) which are in turn a function of the experimental parameters (explosive energy, height of burst, and range). The blast parameters in the database must be consistent with the measured traces and the appropriate scaling theory. This qualification effort provides relations that can check the credibility of field data and provide blast parameters for cases where data are missing.

**Literature Search.** References on blast parameters have been collected and an extensive bibliography compiled. Blast parameters in the free-field (no ground reflection) are in close agreement among the various sources [3]. A complete description of parameters in the Mach Stem region (below the triple point), however, is reported only in one reference. In this region the blasts are considerably stronger. Most of the free-field blast tests were conducted below the triple point and agree with Mach Stem data, while those cases above the triple point agree with free-field results.

**Correlations.** Swisdak [4] provides a complete set of "data" (actually, curves which have been faired through data) in the Mach Stem. We have developed relations connecting peak pressure, positive impulse and positive duration ( $p$ ,  $I$ ,  $t$ ) to the charge weight, height of burst and range ( $W$ ,  $H$ ,  $R$ ) in Sachs scaled dimensionless variables.

A closer examination of the Swisdak "data" revealed that points at small ranges are, in actuality, above the triple point and therefore should not be used to generate correlations for the Mach region. This discrepancy was revealed when the previous correlations were compared with the WRAIR summer study tests. A revised correlation was developed using Kingery's correlation [5] for free-in-air blast parameters corrected for Mach region effects. The agreement with WRAIR field data is now excellent over the entire range of charge weights and distances. See Figure 2.

**EITACC Simulation.** The parameterization of the free-field blast wave relies on many simplifying assumptions and is at best a summary of a particular range of conditions. As we have found, those assumptions are violated in many cases of interest. Other, even more important aspects, such as the reflected loading, have not been sufficiently measured to allow a correlation to be fit. Consequently, it is necessary to have a computational means for determining the blast environment in "free-field" conditions. EITACC was set up for a finite height of burst explosion and the evolving blast field computed. The time of arrival, heights of the triple point, and pressure parameters were in good agreement with the Swisdak curves. Furthermore, insight was gained into the early time blast development and characteristics near the triple point. See Figure 3.

### 2.1.3 Data Retrieval

To understand and effectively analyze the data being generated in the complex wave tests, it must be organized and integrated. In 1991 alone, WRAIR sponsored over 50 field tests using over 120 sheep to study complex waves. These tests were run with over 25 configurations of the test bunker. Each configuration has 9 to 12 pressure gages, the Blast Test Device, and as many as three sheep. Knowledge of the position and orientation within the bunker of each animal and gage is critical to understanding the test results.

As part of an in-house project, JAYCOR has developed the Information Integration System Software (IISYS) to provide the data organization required in such circumstances. IISYS is a system of Microsoft Windows programs to collect, organize, analyze, and view

diverse forms of information. A subset of the system has been applied to the organization of the blast and pathology data. A relational database has been developed for each test that is keyed to the relational database being developed for each animal. A configuration drawing has been prepared for each test. All of the previously scanned photographs have been converted to Windows BMP format. The animal database has been expanded to cross-reference the test database and each photograph and pressure trace related to that animal. Finally all of the data has been organized into a directory structure based on test. See Figure 4.

We have delivered to WRAIR a copy of IISYS and a subset of the data for evaluation. After the organization has been evaluated and comments incorporated, we will deliver the entire database. As of now, the data consists of:

- ☐ 231 record in the Test database (dBase format)
- ☐ 740 records in the Animal database (dBase format)
- ☐ 853 scanned photographs (BMP format)
- ☐ 2002 data traces (GDIF format)
- ☐ 27 configuration drawings (WMF format)
- ☐ 91 hot files (one for each bunker test)

The software includes the following modules:

- ☐ HotSpots (views test configurations and linkage to all data)
- ☐ dbSrvr (displays databases and allows queries)
- ☐ ImgSrvr (displays pictures)
- ☐ TextSrvr (displays text)
- ☐ xySrvr (displays time series plots)
- ☐ Injury (Windows version of INJURY 3.02)

Instructions are provided on installing the program and the data files.

#### **2.1.4 Data Analysis**

JAYCOR has assembled most of the pressure and pathological data from the free-field and complex wave tests conducted at the Blast Test Site. This data has been used to formulate and test the biomechanical models. The pathological scoring has changed in the more recent tests: there is greater detail in describing the nature of lesions, but there is less information on where the lesions occur. To be able to have a consistent basis of comparison of free-field and complex blast exposure, it has been necessary to assign some of the location information based on photographs and pathology notes. As a result, a consistent set of data has been produced.

While the biomechanical models will provide the understanding and predictive ability to anticipate all forms of blast injury, those models are still undergoing development and testing. Some organs, such as the gastrointestinal tract, are emerging as primary injury

sites, but the corresponding models are only partially developed. It is important to evaluate the whole spectrum of blast injury at this time, independently of modeling considerations, so that the trends and relative importance can be assigned.

Previously, we made a preliminary analysis of the data that identified significant trends in threshold levels and injury patterns. A closer examination of the data has been made to correct or eliminate spurious points. The importance of gastrointestinal injury in repeated and complex exposures remains a dominant feature. The result is a comprehensive study of the injury trends that is contained in reference [6].

Even in the free-field, there are still many parameters that can be used to form correlations. A common parameter historically used in blast analysis is the energy density,  $E$ , which is proportional to the charge weight divided by the range cubed. This simple parameter makes it possible to compare most cases and thereby identify underlying trends. The measure of injury was taken as the fraction of animals in each severity class. See Figure 5.

***Injury Severity.*** As expected, injury severity increases with energy density for trachea, lung, and GI. These trends are clearest when the smallest charges are not considered, showing that energy density is not the only scaling parameter. At a given energy density, increasing the number of shots increases the injury severity for the trachea and GI, but not for the lung. This surprising finding implies a difference in the lung's response to fatigue.

***Injury Threshold.*** For a single exposure, the GI and trachea have a higher energy density threshold than the lung. At twenty exposures, however, the lung has the higher threshold. This pattern follows that observed for severity.

***HHA Implications.*** Dodd has proposed defining "unacceptable" consequences to be slight lung or GI injury or moderate trachea injury. Based on these criteria, lung and GI set the limits for single exposure, while GI sets the limit for multiple exposure. If this pattern holds, it will be necessary to develop a better understanding of GI injury to formulate an HHA methodology.

Using the knowledge gained by the screening analysis, the results can be refined by considering a complete set of mathematical scaling parameters. The measure here was the average injury score for each organ.

***Sach's Scaling.*** Dimensional analysis shows that both the energy density and the charge weight are independent scaling parameters for free-field blast waves. The energy density is the most important because it scales the peak pressure, duration, and impulse, while the charge weight to the one-third power multiplies the duration and the impulse. Since any model correlate, such as critical stress or irreversible work, must be a function of these two parameters, then injury must also show this dual dependence.

***Correlations.*** The injury data was divided into both energy density and charge weight classes and the average injury score determined for each cross tabulation. Except for only

a few combinations, the average injury showed a very regular pattern for all cases. Both thresholds and severity increased with both quantities, as expected. Again, the GI and trachea showed increased response to multiple exposures, whereas the lung did not.

The pattern of injury within the organ is important to interpreting the significance of the injury and the possible extrapolation of the results to man.

**Gastrointestinal Tract.** Injury distribution by organ was analyzed for two ranges of charge weights where most tests had been conducted. Most of the intestinal sections from the large colon to the ansa spiralis are similarly injured, with the large colon being the most vulnerable. The pattern follows that of the overall GI grade, but the exact relation should be further refined (see earlier discussion). The rectum and anus sustained only low level injury, while the ileum and jejunum were not injured at these test conditions. Only the liver of the solid organs and the abomasum of the stomachs showed injury, which was slight.

## 2.2 Blast Field Simulation

### 2.2.1 Simulation of "Task Order 4" Geometry

Task Order 4 is a test series designed to set safe exposure levels for future human volunteer studies. A blast from a charge outside is introduced into an 8' x 8' x 10' room through an 8" pipe. In the simulation, the rectangular room was approximated by a cylindrical room with the same volume and length, but the details of the external geometry surrounding the charge were included. See Figure 6. The calculations were made on a grid with 1" spacing which has been shown to capture the most interesting blast features.

The simulation shows that the blast exiting the pipe has a spherical shape but varies strongly with angle. See Figure 7. A complicated reflection pattern develops that produces the largest pressures at certain focal points and a times later than the arrival of the first waves. One strong focal point occurs where the pipe passes through the wall, which might be the location of a soldier firing a weapon from the enclosure. The agreement with measured data is quite good. For the first 40 ms, the calculation and data show nearly identical patterns of peaks and pauses. The impulse over this time is also closely followed, showing that the average pressure level is also being reproduced. After 40 ms, the calculation shows continued oscillation of approximately the correct level, but no longer in phase with the data. The impulse after 40 ms. begins to deviate significantly: the calculated impulse continues to increase due to pressurization, while the data steadily decreases, perhaps due to room venting.

In the free-field, the blast propagates in a spherical shell causing the energy density to decrease as the cube of the distance. This behavior leads to Hopkinson scaling: blast strength is proportional to the cube root of the charge weight. For Task Order 4, since the collector captures most of the blast energy, the blast strength should be in direct proportional to the charge weight, which is confirmed in simulations made with 0.5 and 1.0 lb. charges.

### 2.2.2 Simulation of RAAWS

The free-field firing of the RAAWS weapons produces a complex wave form, arising from the multiple blasts due to the shock wave from the round, the exhaust of gas from the rear, and the escape of gas from the front, as well as subsequent ground reflections. The pressure varies considerably at different crew positions and with soldier orientation (kneeling, sitting, and prone). Currently, only "incident" pressure gages have been used, so it is difficult to translate the measurements into load. Multiplying the traces by the usual free-field factor may well be overestimating the load. Treating the traces as load, however, may be an understatement. A CFD simulation can clarify the situation.

An EITACC simulation of an explosion in a tube of the same dimensions as the RAAWS has been made in order to characterize the variation of blast strength with angle. The calculations show the usual propagating blast wave and a ground reflection followed by an unusually large underpressure caused by the overventing of the tube. These characteristics are seen in the RAAWS data. When three such blast events are superimposed, each with a different blast strength and timing, a signal suggestive of the RAAWS pressure measurements is obtained.

The EITACC simulations were continued using more accurate information on the location of the pressure probes and the height of the weapon above the ground for each test configuration. The superposition of EITACC solutions not only reproduces the general character of the data, but captures the variation of the signal as the vertical position is changed. If the blast waves is characterized by a Friedlander shape, the effects of vertical position changes on the timing of the different components can be seen. See Figure 8.

### 2.2.3 M109 Simulation

A current activity at the Blast Test Site is the simulation of blast environment in and around the cab of the M108/109 caused by the firing of its 155 mm weapon. Like the M198 studied over a decade ago, this weapon has a muzzle brake with redirects part of the explosive gasses back toward the crew area. The goal of the test is to reproduce the blast without using an actual weapon firing.

Initially, detonation of bare charges at a distance from the crew compartment were tried by the pressure signals did not resemble those measured around the actual weapon. JAYCOR's computer simulations showed that the long, negative phase of the wave could only be achieved if the blast vented from a tube. Following telephone conferences, it was decided that a systematic computational investigation would be conducted at JAYCOR and at the Department of Respiratory Research to provide an understanding of the basic phenomena and the parameters controlling the far field wave. In the meantime, the Blast Test Site personnel would continue to gather data on various physical configurations, guided wherever possible by the computational results.

The computations have shown that the blast field is primarily controlled by the magnitude of the explosive placed in the tube and only weakly depends on the diameter and length of the tube. The duration of the negative phase grows with distance, therefore suggesting a greater standoff than was originally tested. Finally, the blast wave varies rapidly with angle. Straight ahead, a strong second shock forms that is very different in character from the blast wave propagation in other directions. A brief report on these findings has been prepared.

#### **2.2.4 Computational Fluid Dynamics Support**

As part of JAYCOR's support to WRAIR during the current contract, we are making available a single machine version of our EITACC program for simulating blast waves in specific geometries of interest. The program has a graphical interface that allows the user to set up problems for these geometries and vary certain geometric elements, charge characteristics, and probe locations.

The interface with the EITACC program is designed to allow the user to make blast simulations without having a detailed knowledge of the underlying mathematical solution procedure or its particular computer implementation. Nonetheless, some background material to the subject of Computational Fluid Dynamics (CFD) will be useful to understand the strengths and limitations of the method. A brief summary has been prepared to provide a starting guide.

EITACC employs a very powerful and generalizable method of solving the fluid dynamics equations that has been applied to engineering problems in chemical plants, aerodynamics, underwater missile launch, as well as blast simulation. A brief summary of the solution technique is presented that can be best appreciated after the general introduction to CFD has been absorbed. Also included are selected references to theory and applications of the program.

The graphics-based user interface to the EITACC program has been customized for WRAIR's use. The package includes a problem setup module, the EITACC program, and modules for visualizing the computational results. The package runs on an HP Apollo workstation under the UNIX operating system. The hardware and software requirements have been provided to WRAIR to assist them in acquiring the correct configuration. The users manual provides a detailed description of all of the program options.

The interactive version has been used to compute the free-field, bunker, and Task Order 4 problems previously reported in order to validate the proper behavior of the EITACC-BL program in the form to be delivered to WRAIR. A description of those results and visualizations of calculations has been included. These problems will also serve as examples for WRAIR to practice with and to confirm the correct operation after EITACC-BL is installed at WRAIR.

The program has been installed at WRAIR. Training has been given to WRAIR staff and we will continue to help as the program is used [7].

## 2.3 Injury Model Development

### 2.3.1 Generalized Fatigue Model

The fatigue model proposed originally assumed that the critical stress decreases linearly with repetition until an "ultimate strength" is reached. This model was successful in explaining the qualitative trends seen in URT injury in animals. It was presumed that the same fatigue reduction in critical stress occurs in other organ systems, but we have shown that the fatigue factor for the lung is much smaller. In fact, based on the currently available data, we cannot find a significant nonzero value. Conversely, data clearly indicates that the gastrointestinal tract shows significant fatigue effects.

A generalization of the fatigue relation that is consistent with that used for non-biological materials:

$$\log\left(\frac{\sigma_N}{\sigma_1}\right) = a - f \log(N + b)$$

where  $\sigma_N$  is the stress that will cause injury for  $N$  exposures,  $\sigma_1$  is the stress that causes injury from a single exposure, and  $a$ ,  $b$ , and  $f$  are constants. This relation produces a smooth, S-shaped curve.

The URT data has been re-examined for fatigue effects. A best fit of average injury score to the maximum equivalent stress shows the expected log-normal behavior for each number of exposures (1, 5, 20, 100). See Figure 9. Those curves provide the data to determine the coefficients in the fatigue relation. The fatigue factor for 100 shots, for example, is 0.4, that is, the stress required to produced injury is reduced to 40% of its single shot value.

### 2.3.2 Foam Experiment Results

Under blast loading, the rapid motion of the chest wall compresses the parenchyma in the vicinity of the pleural surface and raises the local pressure. That pressure is a significant force in slowing down the chest wall and must be accurately represented in the modeling to obtain the correct chest wall dynamics. Furthermore, that rapid compression can do damage to the parenchyma and the work done by that force is used as a correlate of lung injury. It is the purpose of this subtask to refine and finalize these ideas for use in the injury prediction methodology.

In a previous contract, a physical model of the chest wall-lung interaction was developed using a moveable piston to compress shaving foam. Tests were conducted to show

that the material properties of the foam were comparable to lung parenchyma. In those tests the piston was instrumented with pressure transducers and accelerometers to relation between chest wall motion and lung pressure. The pressure measurements were difficult and a completely satisfactory confirmation of the complete dynamics could not be achieved. In this subtask, a redesigned test configuration that does not require pressure transducers is used to extend the earlier findings.

**Kinematic Approach.** An instrumented falling weight is used to deliver the loading to the lung surrogate. By measuring the motion of both the weight and the piston it is possible to determine all of the kinematic quantities needed to evaluate the energy equation. See Figure 10. The work done against the surface pressure can be confirmed by computation. All of the material properties (density, sound speed, and compressibility) were remeasured.

**Energy Conservation.** Over 60 tests were conducted and energy conservation was demonstrated to within about 5% for all of the tests analyzed in detail. This agreement is well within the expected scatter of the material properties and confirms the  $p = \rho c v$  assumption for low velocities. The results also show that in the nondissipative foam, that the piston work is translated into wave motion that can reflect back to the piston at later time. A closer examination of the dissipation mechanism in lung parenchyma is called for.

**Kevlar Effects.** Eighteen tests were conducted in which the weight struck the target covered only with a thin fabric layer and sixteen tests with the target covered with layers of kevlar material. The kevlar targets showed an average of 13% more work done on the foam. A t-test analysis showed the results to be highly significant ( $p = 0.01$ , for two-tails). Furthermore, this increase is about the same size as the injury increases observed in the field. This encouraging trend suggests such tests could be used to screen materials for blast effects.

### 2.3.3 Extension of Piston Model

The heart of the localized model, used by the INJURY program to compute lung injury, is the relation between chest wall motion and pleural surface pressure, that is,  $p = \rho c v$ . The mathematical form was suggested by a heuristic argument and is an approximation that occurs in many fluid dynamic situations. The foam experiments and numerical calculation also support this relation, however, under extreme loading that produces chest wall velocities about the wave speed, there is theoretical reason to question the relation. Experiments to directly measure the dynamics in these extreme ranges have not yielded conclusive results. This subtask is intended to provide a solid theoretical basis for the term and to suggest the behavior at large velocity.

**Theoretical Derivation.** Based on an analogy with gas dynamics, the pleural pressure relations were derived exactly. The result is a more complicated formula for the pressure, however, for velocities small compared to the compression speed the formula reduces to  $p = \rho c v$ .

**Effect on Work Calculation.** Calculations were made with the approximate and exact relations for a variety of Friedlander waves. The exact relation predicts a smaller work value, 5% smaller for peak pressures under 100 kPa and as much as 25% smaller for peak pressures around 800 kPa. The final version of INJURY will incorporate the exact relation.

#### 2.3.4 Lung Injury Model

The lung injury model provides a correlation between the mechanical work done on the lung by the blast-caused acceleration of the chest wall overall lung pathology. The model has been refined to the point where it captures the results of all previous blast tests.

**Normalized Work.** A subtle, but important refinement has been made to the lung injury prediction model. We have been computing the energy in the compression wave caused by the external blast loading and have achieved good correlation with injury for sheep. We have been using a single pressure loading, but have discovered that the variation around the body, in the free-field as well as in enclosures, is considerable. Therefore, the procedure was modified to use four pressure load (as recorded by the Blast Test Device or inferred in free-field cases). The agreement with data was considerably improved and the ambiguity of the choice of a single probe eliminated. Furthermore, we have selected normalized work = total wave energy / (lung volume \* atmospheric pressure) as the dimensionless correlate of injury. This form allows us to take into account body mass, which also improves the correlation. See Figure 11.

**Species Scaling.** All of the data collected at the Blast Test Site under MRDC programs has involved sheep, but the final use of the models is to make predictions for man. The extensions of the model to normalized work coupled with scaling laws for the model parameters based on total body weight allows the model to be applicable to all species. See Figure 12. As expected, smaller animals are more vulnerable. Now we can make predictions specific to man.

**Lethality.** We returned to the lethality results reported by White, et al. from animal tests conducted before the MRDC programs. These tests used many different species and many different exposure conditions and collected statistically significant numbers of data so that lethality correlations could be developed. Unfortunately, the exact conditions of the test were not recorded so that we have only the peak pressure and duration of the exposures.

Nonetheless, we were able to reconstruct much of the tests and compare the results with our biomechanical model. See Figure 13. Lethality is shown to be predictable by normalized work and forms an incidence distribution that parallels the various injury levels. Other anecdotal findings on the effect of the pressure wave form on lethality were also reproduced.

**Lung Injury Model Paper.** The advances in the lung injury model made during the last half year have brought the model to a very satisfactory state of validation. A manuscript

describing the model and its validation against data has been prepared and submitted to the Journal of Biomechanics [8].

**INJURY Model Review Meeting.** On April 11, 1994 a meeting was held at WRAIR to introduce the potential users of the INJURY software to the theory and validation of the model. As a result of the discussion, JAYCOR is preparing a plan to produce version 4.0 which will incorporate the latest model, have a well-defined data input specification, and appropriate documentation. The contract representatives stated that the program will be Government property to be distributed only on a contract-need basis, not for general distribution. It was pointed out that the mathematical equations, since they will be published in the scientific literature, would be available to anyone. It has not been decided whether the program should include tympanic membrane rupture and tracheal injury, since these models have not received the same scrutiny as the lung model.

## 2.4 Health Hazard Assessment

The goal of the HHA methodology is to define the level of risk associated with a particular blast overpressure exposure. One part of the effort is directed to understanding the relation of the external blast overpressure to a specific injury (URT, lung, GI, auditory) in an individual. The other part of the effort is to translate those results into an estimate of risk to a population from all of the injury paths.

Historically, nonauditory HHAs were based on an estimate of the "threshold" injury to a single organ system (usually the lung). The threshold level was not established by statistical analyses, but by an estimate intended to be just "below" (in peak pressure-impulse coordinates) any injury previously observed. The fraction of the population that will be injured below this level will depend on the number of animals used in the tests.

Recently, Dodd proposed that an "unacceptable" exposure be based on the occurrence of any lung or GI injury or moderate URT injury. A curve in peak pressure-impulse coordinates was selected as a "threshold" for free-field exposures. While this formulation takes into account multiple organs it also does not account for statistical effects. Both of these approaches are limited to simple free-field waves which can be described by two parameters.

For the RAAWS HHA, Dodd offered a further refinement by using the incidence rates computed by the INJURY program to define an occupationally unacceptable situation as one that produces 1% incidence of lung injury or 10% incidence of trivial URT injury. This approach uses the biomechanical measures of injury correlation, so it can be applied to all blast situations, and it attempts to account for population effects, thus reducing the influence of the number of animals in the tests.

### 2.4.1 Current HHA Methodology

WRAIR has been making HHA on a variety of weapon systems for the past 10 years. Early assessments were made with animal tests and man-rating studies. More recently, an attempt has been made to use the quantitative predictions of the INJURY program in the assessments. This approach is in its formative stage and the use of the predictions is more heuristic than systematic. With the change over of personnel at WRAIR, it is critical that the current methodology is defined precisely so that additional analyses, especially on the RAAWS, can be continued in a consistent manner.

**Collect and Organize RAAWS Materials.** All of the materials associated with WRAIR's evaluation of the RAAWS system were collected. The methodology and the process of determining the Round-Per-Day (RPD) limits for that system were reviewed. The auditory limit is determined by the W-, X-, and Y-curves in Mil-STD-1474C. The nonauditory limit is determined from the analysis of URT and lung injuries predicted by INJURY 3.2. Specifically, the RPD limit is the maximum number of exposures to the same blast wave that leads to either a URT injury of 10% or a lung injury of 1%. Within each group of shots with the same position and round type, the worst case with one, two, and six exposures are considered.

**Reproduce Previous Analyses.** The previous results were checked by rerunning INJURY 3.2 for all of the test records. A batch process was devised. We found agreement with WRAIR's analysis, except one case where an inconsistent time interval was used. The previous analysis was limited to the single significant figure displayed on the INJURY output screen. When the analysis was made using more significant figures and when the cases of three, four, and five shots were considered, we arrived at a slightly different set of RPD limits.

### 2.4.2 Refined HHA Methodology

A completely general, statistically correct HHA methodology has been formulated. The HHA is stated in the form: "a given blast overpressure environment will produce X% incidence in the population of any one of a number of unacceptable injuries." The mathematical formulation incorporates the statistical distribution of injury for each organ system with its mechanical correlate, the statistical scatter in the mechanical correlate due to the scatter in the measured pressure traces, and the statistical combination of injury among organs. The end result is a methodology that can be readily expanded to other organs (such as GI and auditory), produces an objective measure, and provides a measure of the level of confidence in the incidence and a quantitative means to determine which elements contribute to the uncertainty.

The mathematical derivation of the relations is contained in the attached sections. The heart of the derivation is the convolution of each statistical distribution. The final formulation must be integrated numerically.

In order to apply the methodology to the RAAWS, it was necessary to recalibrate the correlations for moderate URT injury and slight lung injury at low stress and work,, respectively. Since the HHA deals with very small incidence, the dose-response curves in these regions are critical. In redoing the correlations, a complete statistical accuracy determination was made.

Furthermore, it was necessary to develop a correlation for GI injury. Currently, INJURY uses a Bowen correlation that can only be applied for single shot cases (since there is no fatigue theory for the Bowen correlation). Not only are we interested in multiple RAAWS exposures, but the Bowen correlation proved to be very poor even for single shot. In the absence of a mechanical theory, we correlated GI injury to work, arguing that GI and lung injury have occurred at much the same levels in simple free-field cases. Clearly, this is not a desirable long term assumption.

Finally the statistical distribution of mechanical correlates (stress and work) were determined for the RAAWS data. In the past, only "selected" traces were used. Now, all of the data is used on equal footing.

The results are presented below. Note that 1% total incidence using the refined methodology has nearly the same values as the previous RAAWS analysis made with the subjective criteria (shown in parentheses).

Number of rounds to produce 1% incidence			
Position	HEAT/TP	Screening	HE
Prone	0 (0)	4 (3)	6 (3)
Sitting	1 (2)	5 (6)	3 (2)
Kneeling	6 (6)	6 (6)	6 (6)

Now we can evaluate the confidence of these results, taking into account the statistical scatter in the injury correlations and the scatter between successive shots. The details are in the accompanying report, but roughly speaking these number of rounds could produce 3% incidence of injury at the 68% confidence level and 10% injury at the 95% confidence level. As with most low incidence estimates, there is a considerable amount of uncertainty.

This uncertainty can be removed by examining the source of the variation and then proposing additional tests and analysis that will reduce the most important ones.

### 3. Conclusions

Significant progress has been made toward the four goals of the project. A summary of that progress and the specific areas to be pursued in the second half of the project are listed below.

#### 3.1 Progress Toward Goals

***Extended Pathology Database.*** All of the physical and pathological data from free-field and the complex waves studies have been placed in a common database format. Pathology data has been regraded so that uniform model comparisons can be made. Pressure data from the blast tests have been qualified, using either measured traces when available or by reconstructing idealized traces from test conditions. The data has been extensively analyzed for trends that are independent of modeling theories. The results show the importance of gastrointestinal injury as a threshold indicator and the redistribution of injury in complex wave environments. The data has been placed in formats that are accessible by MicroSoft Windows programs and JAYCOR's IISYS data management program is being tested as a vehicle for accessing all of the information.

***Blast Modeling.*** Computational Fluid Dynamics has been used to reproduce and understand several complex blast situations: the region near the triple point in free-field blast, the distribution inside the room for the bunker studies and Task Order 4, and a preliminary understanding for the blast around the RAAWS weapon. A version of EITACC is at use at the Department of Respiratory Research of WRAIR for in-house analysis of blast conditions.

***Injury Modeling.*** The fatigue model for URT injury has been extended. The pleural surface dynamics model for predicting lung injury has been significantly extended. Four pressure traces, one for each body quadrant are used in the calculation of work. The parenchymal wave calculation has been generalized to include nonlinear wave phenomena. The correlate of injury has been generalized to normalized work, work per lung volume and atmospheric pressure, which allows the correlation to be extended to other species and test locations. A correlation has been developed for each level of lung pathology and for lung area injured. Correlations have also been developed for lethality and several anecdotal trends have been reproduced. The model has been described in a paper submitted for publication. Preliminary agreement on the first version of the INJURY program to be released outside the Medical R&D Command has been reached.

***Health Hazard Assessment Methodology.*** Previous HHAs that were made on an ad hoc basis have been reproduced independently and a probabilistic methodology has been proposed that produces similar assessments. A formulation for implementing the

methodology has been conceived and presented to the user community. The formulation was well received.

**Extended INJURY Program.** A MicroSoft Windows version of INJURY 3.02 has been produced that works in conjunction with the IISYS data management system as well as a stand alone program. The user community has expressed a desire to make their own INJURY assessments, so a plan to release a version has been made.

### 3.2 Plans for Second Half of Project

**Extended Pathology Database.** The previous effort has concentrated on collecting and organizing historical test data and in creating uniform free-field and complex wave pathology records so that model calibration can be made. Because grading systems have changed several times and because the grading system has still not been standardized, data remains fractured and difficult to access. This task area will concentrate on creating a unified pathology data system.

- |     |                                  |   |
|-----|----------------------------------|---|
| 1.1 | Scoring System.                  | Establish a pathology scoring system that reflects the "best" pathology, but remains consistent with historical data. |
| 1.2 | PATHOS 2.0.                      | Modify PATHOS program to run under Windows and use the new scoring system.  |
| 1.3 | Consolidation of Data.           | Transfer all data into new system.  |
| 1.4 | Document PATHOS 2.0 and release. |   |

**Blast Modeling.** The previous effort has shown the usefulness of blast simulation in guiding experiment and interpreting data. The Task Order 4 study, the RAAWS tests, and the on-going Task Order 2 tests have shown the need to understand the behavior of blast from a tube. Furthermore, the pressure signal inside a vehicle differs considerably from that of the blast passing by outside, so there is need to better understand the coupling between the two and the importance of internal geometric details.

- |     |                              |  |
|-----|------------------------------|--|
| 2.1 | Blast Tube Simulation.       | Use simulation to develop the general characteristics of blasts from a tube and guidance for experimental testing. |
| 2.2 | Weapon Specific Simulations. | Use simulation to analyze test data from weapons such as the RAAWS, M108/109, etc.                                 |

**Injury Modeling.** The previous effort has established the viability of correlating gross lung pathology with total work done on the lung. The distribution of injury, which plays an important role in complex wave environments, has not been understood theoretically. To capture this effect, a multi-dimensional biomechanics response model must be made. Furthermore, the tracheal injury model must be calibrated against animal test data so it can be used reliably in the INJURY program. Finally, the biological fatigue model should be

extended to include temporal effects, in order to see if certain field observations can be reproduced and whether a rational criteria for the period of occupational exposure can be developed.

- 3.1 3D Thoracic Model. Extend the biomechanical simulations to three-dimensions, using medical imaging as a basis, to see if lung injury distribution can be understood.
- 3.2 Finalize Trachea Model. Calibrate the tracheal injury model against the full animal database.
- 3.3 Biological Fatigue Model. Extend the biological fatigue model to temporal effects and compare with test data.

**Health Hazard Assessment Methodology.** The groundwork for a probabilistic HHA has been established in the previous effort. The mathematics must be made precise and implemented in a computer program so that its impact on HHA can be determined. When the appropriate policy decisions have been made, the methodology should be published and a revised Military Standard promulgated.

- 4.1 HHA Methodology. The mathematical development of the probabilistic methodology must be completed.
- 4.2 Computer Implementation.

**Extended INJURY Program.** The current INJURY, version 3.02, was designed for free-field waves and uses only a single pressure trace. The program should be upgraded to use four traces and make the injury and lethality correlations based on normalized work. After the tracheal injury model is refined, it should be included. In response to the recent injury workshop, a version of INJURY should be prepared for release to the appropriate military community. Both of these versions should have user documentation and should have a standard data input format for pressure traces. Finally, with the HHA methodology is automated, INJURY should incorporate this model.

- 5.1 INJURY 4.0. This version of the program will be released to the blast community on an as-needed basis. It will be restricted in features as directed by MRDC.
- 5.2 INJURY 4.5. This version of the program will be for internal MRDC use and will contain all predictions and outputs needed for HHAs.
- 5.3 INJURY 5.0. This will be the final version of the program and will contain the automated HHA methodology.

## 4. References

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Figure 1. Example of pressure signal compressed from 32,000 data points to 730 points using the TDR programs.

Figure 2. Nondimensional correlations for free-in-air and Mach stem regions.

Figure 3. EITACC simulation of Mach stem evolution for a 3.0 ft height of burst. Dashed curve denotes measured data from Swisdak for the triple point loci.

Figure 4. Schematic diagram of IISYS data management system.

Figure 5. Statistical variation of injury for free-field shots.

Figure 6. Computational grid for simulating the Task Order 4 tests.

Figure 7. Nonuniform spherical blast emanating from the Task Order 4 blast tube.

Figure 8. Pressure data for RAAWS weapon taken at gunner's chest compared with superimposed Friedlander waves and with EITACC simulations.

Figure 9. Correlation of injury from repeated exposure with material fatigue.

Figure 10. Energy partitioning during impact.

Figure 11. Correlation of normalized work to the lung due to blast loading with observed pathology.

Figure 12. Correlation of normalized work with observed lethality for all species.

Figure 13. Correlation of normalized work to the lung due to blast loading with observed lethality.

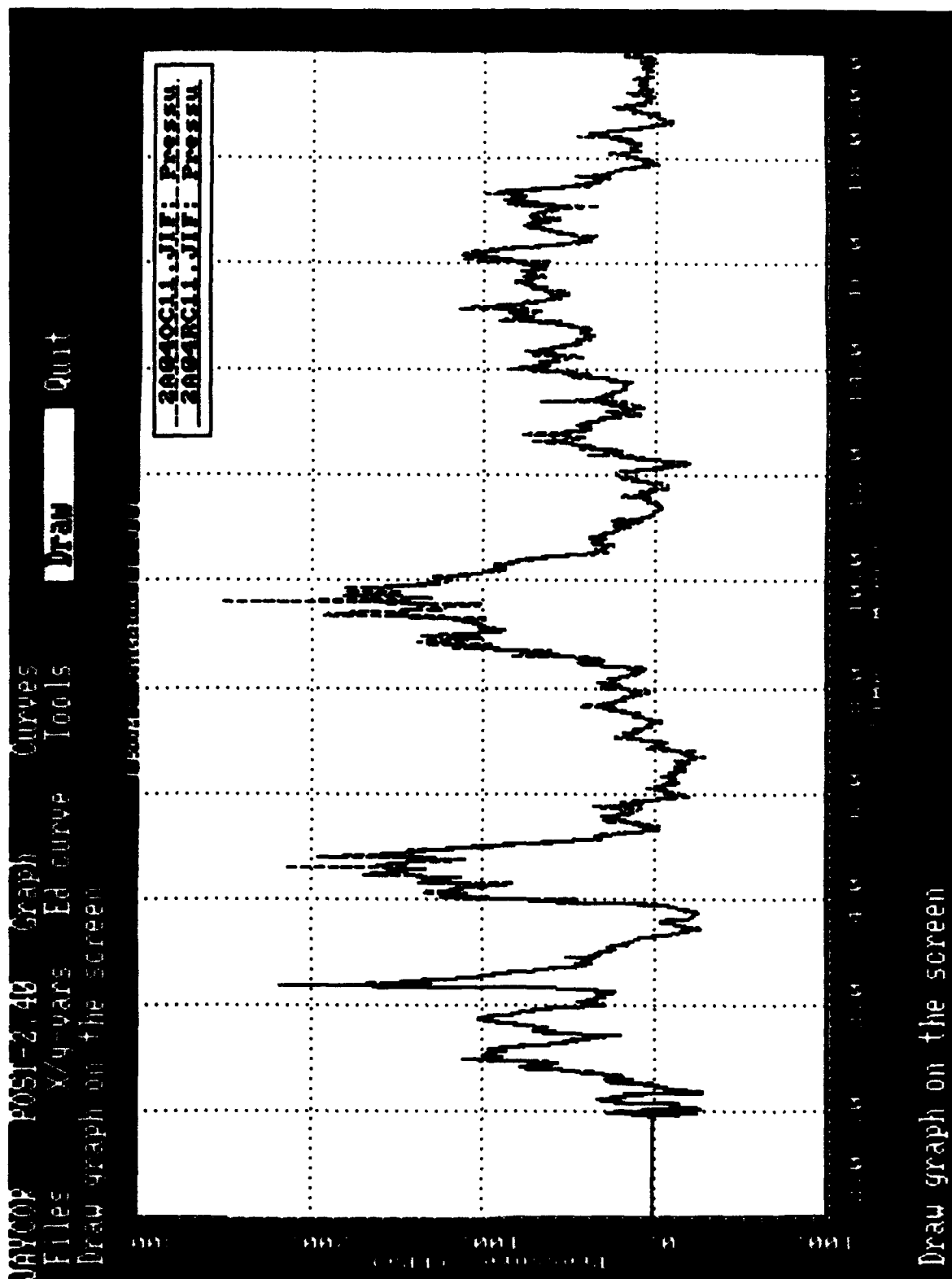


Figure 1. Example of pressure signal compressed from 32,000 data points to 730 points using the TDR programs.

## Nondimensional Peak Incident Pressure

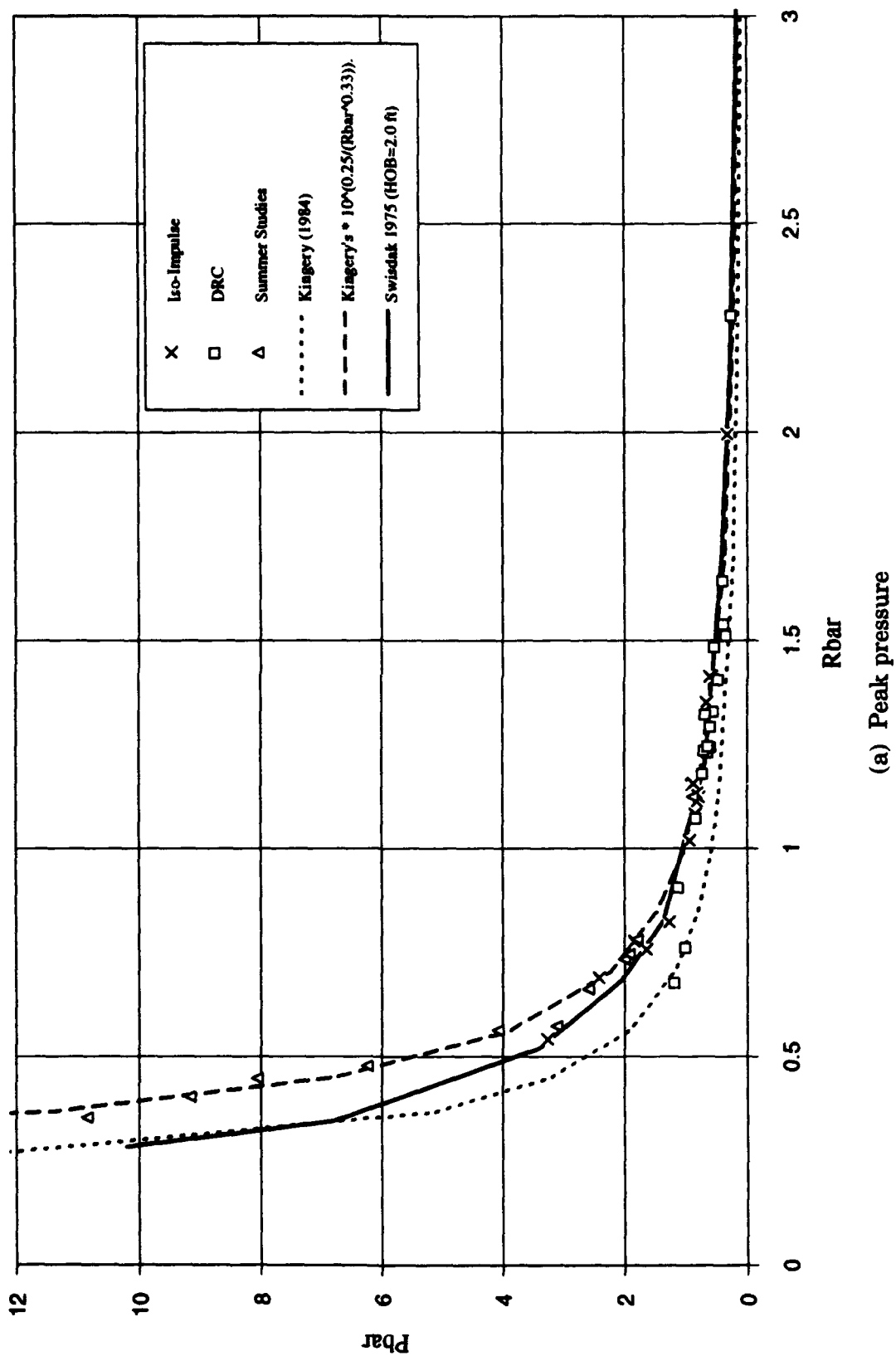
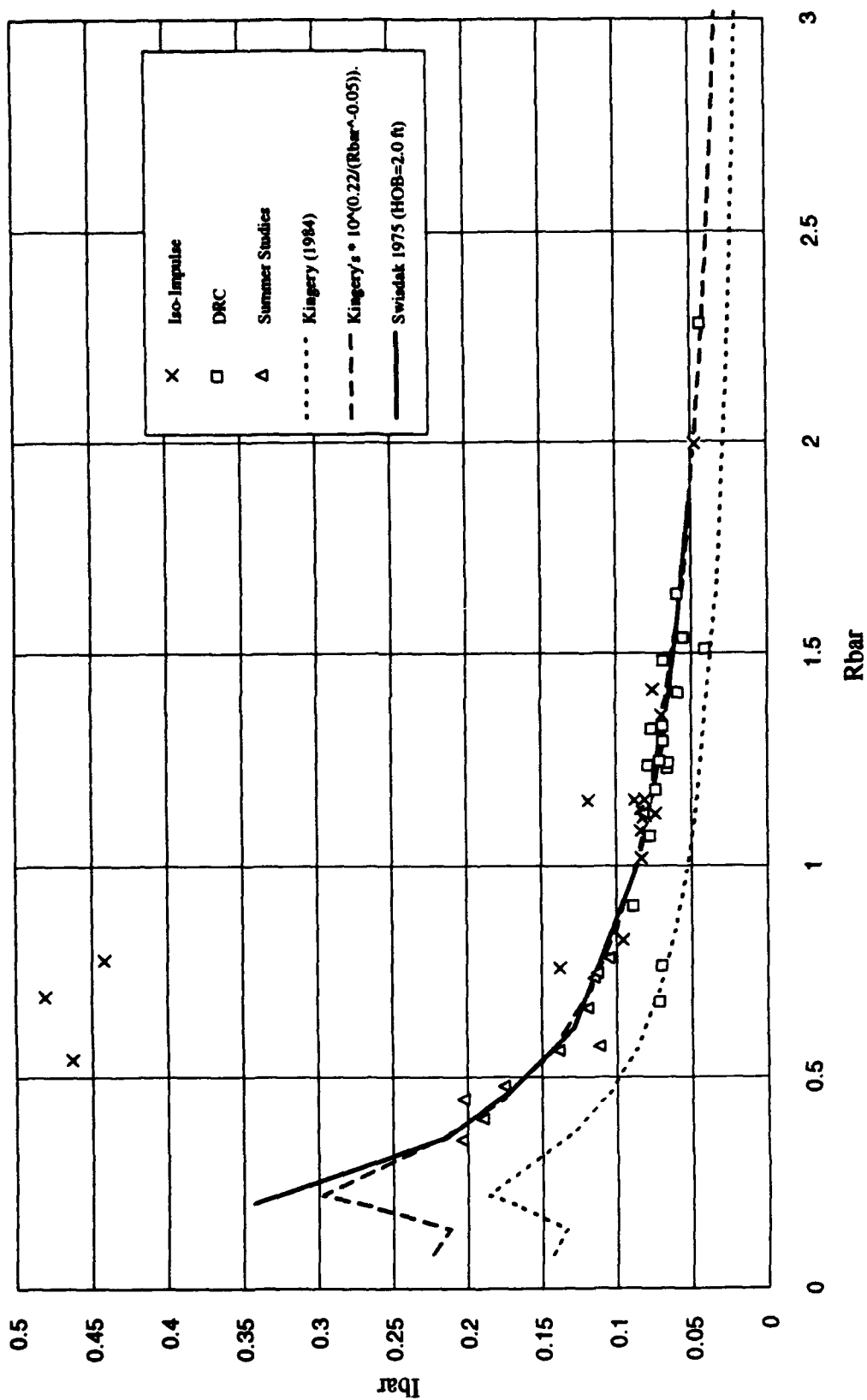


Figure 2. Nondimensional correlations for free-in-air and Mach stem regions.

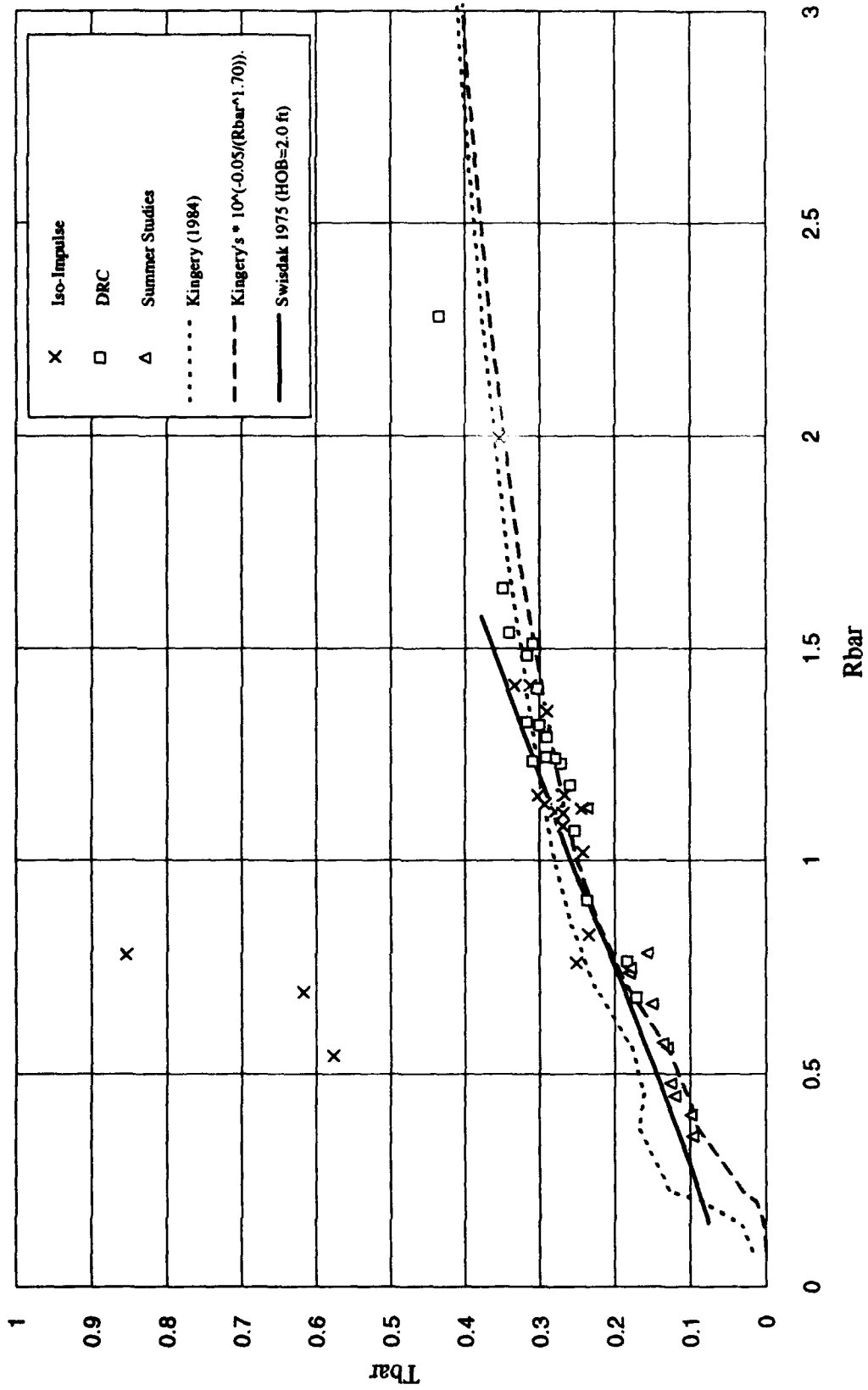
# Nondimensional Positive Impulse



(b) Positive impulse

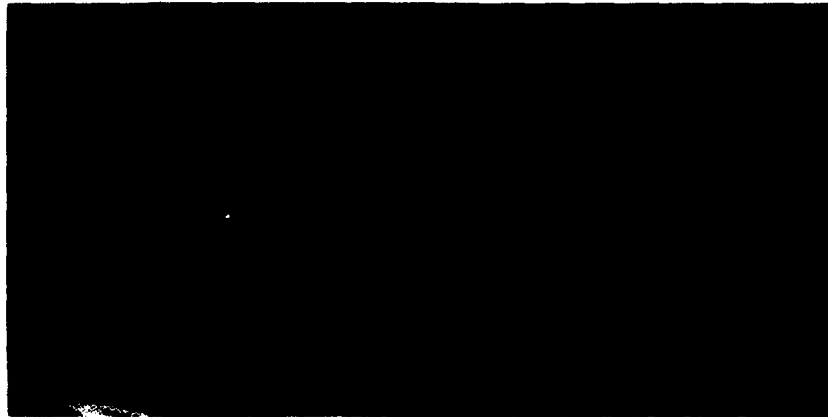
Figure 2. Cont'd.

# Nondimensional Positive Duration

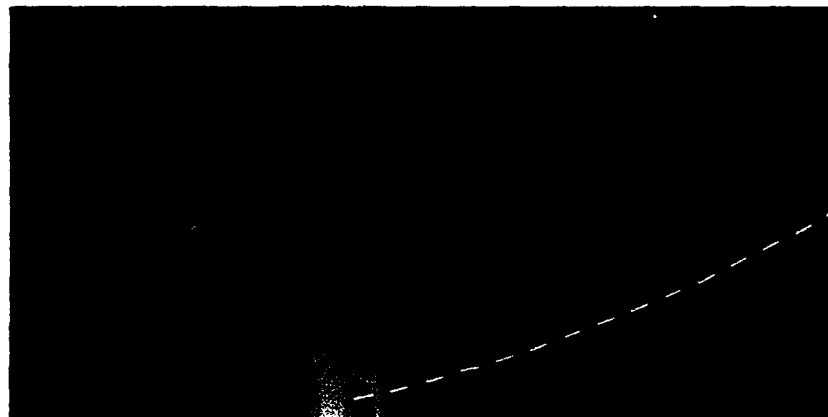


(c) Positive duration

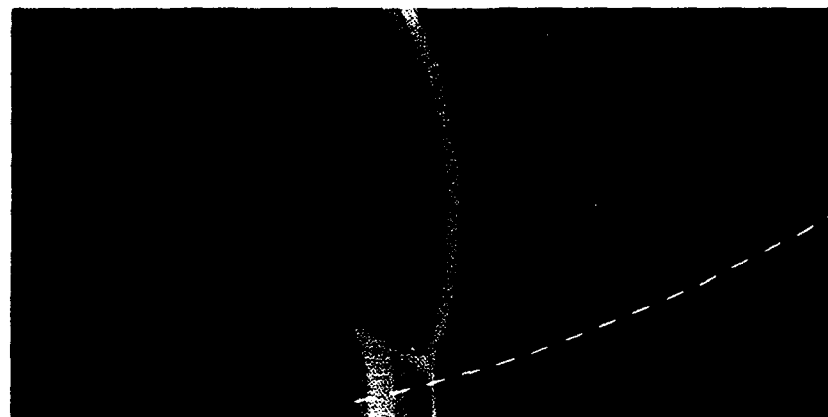
Figure 2. Cont'd.



(a) Time = 0.8 ms

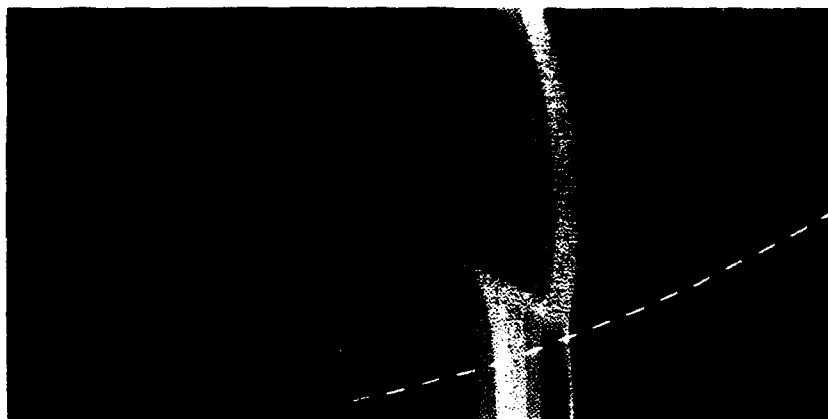


(b) Time = 2.0 ms



(c) Time = 2.4 ms

Figure 3. EITACC simulation of Mach stem evolution for a 3.0 ft height of burst. Dashed curve denotes measured data from Swisdak for the triple point loci.



(d) Time = 3.6 ms



(e) Time = 5.0 ms

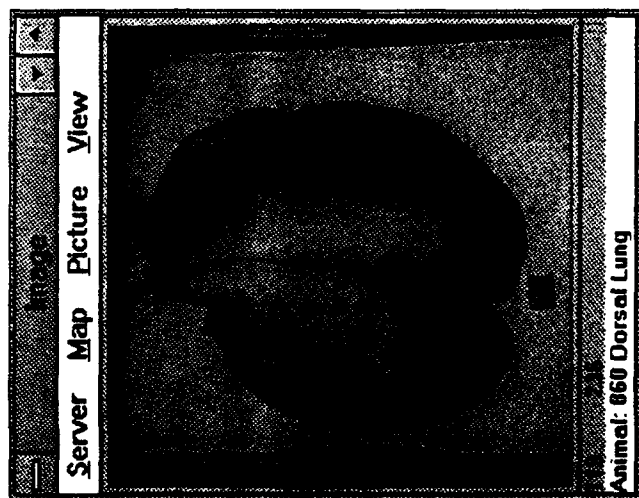


(f) Time = 6.6 ms

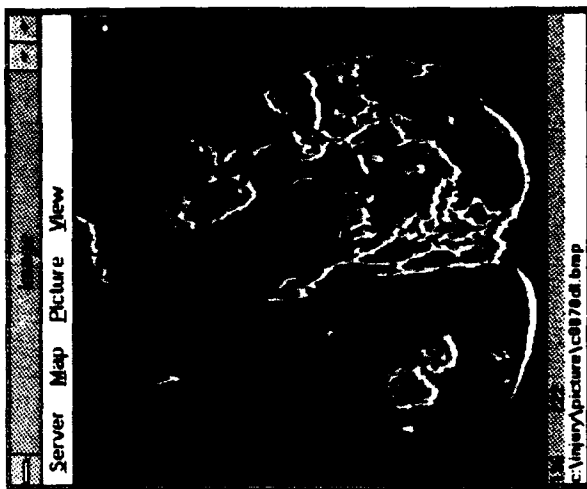
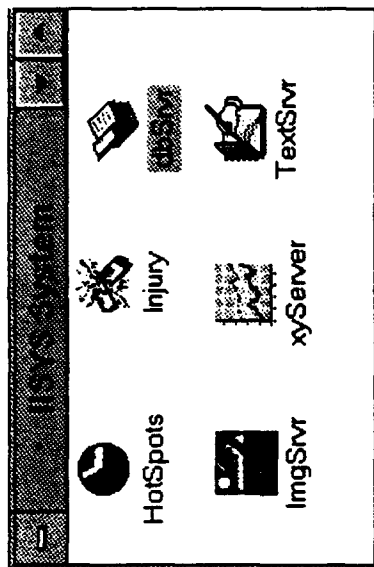
Figure 3. Cont'd.

# JAYCOR

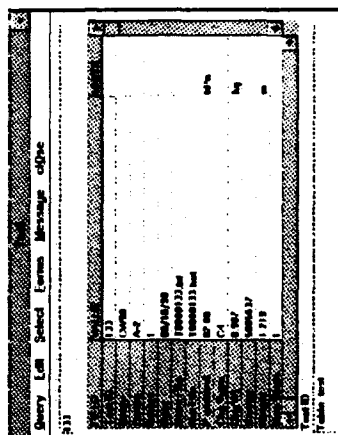
## INFORMATION INTEGRATION SYSTEM SOFTWARE (IISYS)



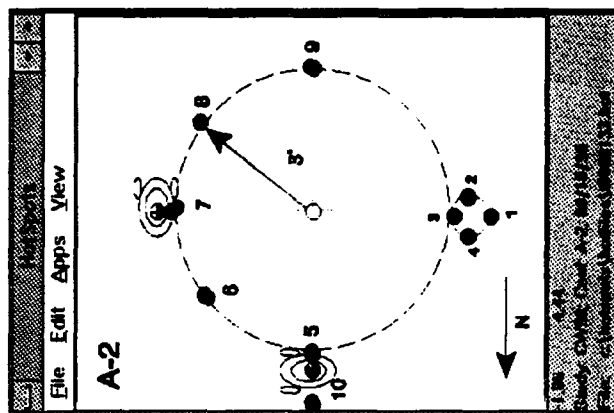
Pictures/Movies



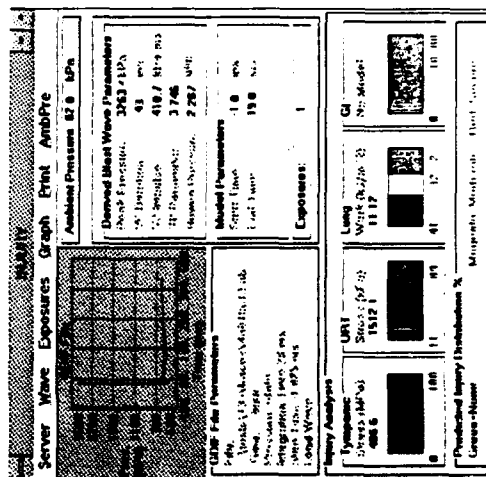
Classified Image



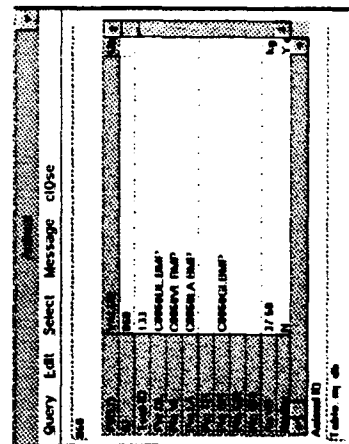
Test Database



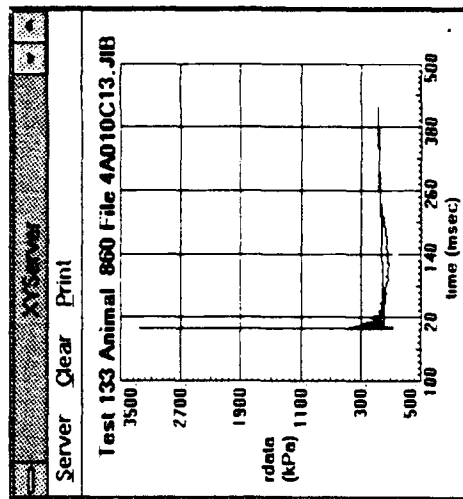
Test Configuration



Custom Applications



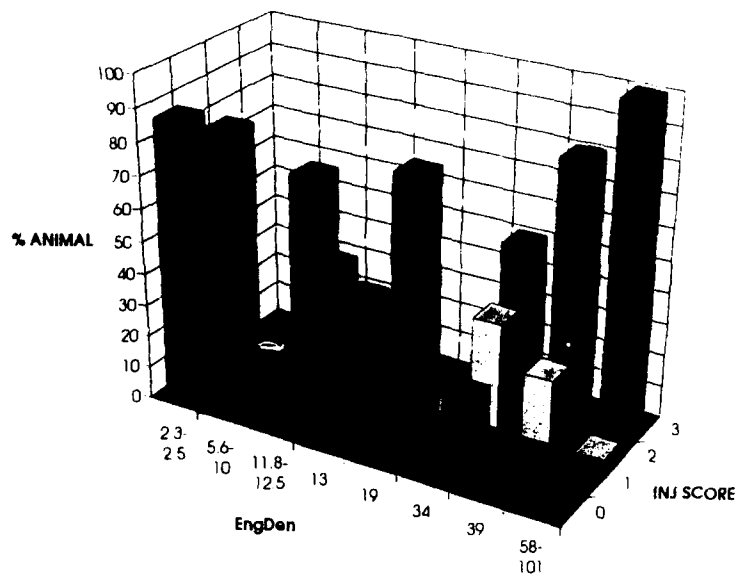
Animal Database



X/Y Plots

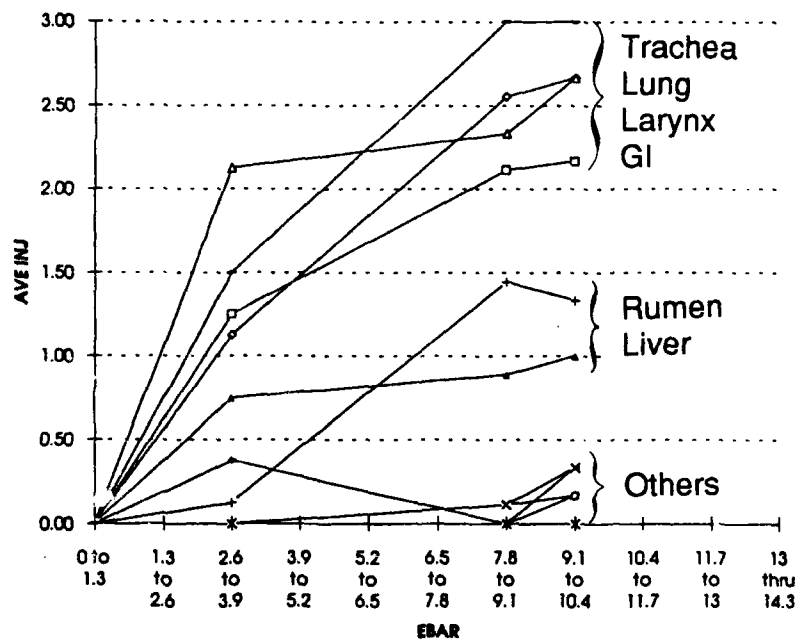
Figure 4 Schematic diagram of IISYS data management system

## 20 SHOT TRACHEA /FF



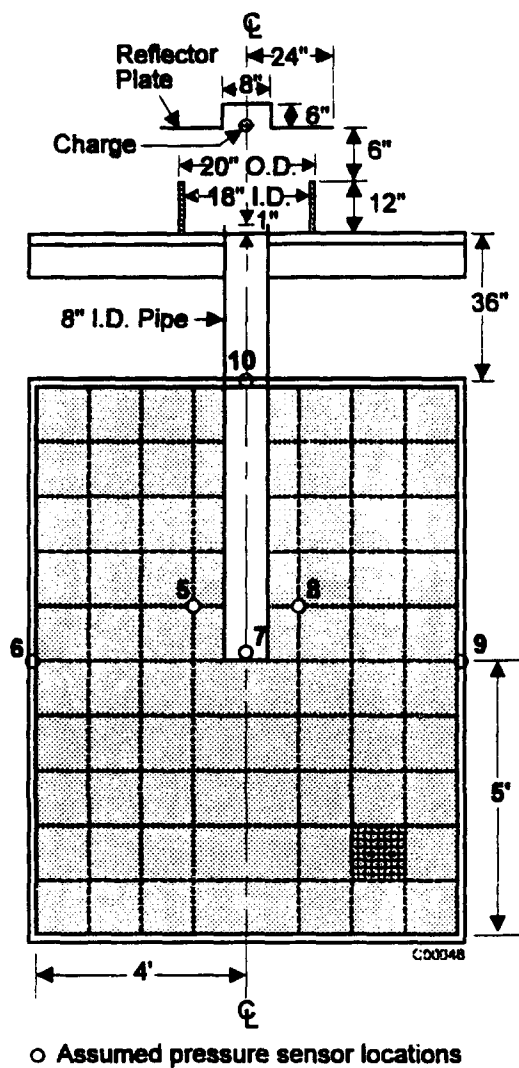
## Statistical Progression of Injury

## 1 SHOT /FF



## Variation in Organ Sensitivity

Figure 5. Statistical variation of injury for free-field shots.



Task Order 4 Mesh  
80(x) × 1(Y) × 205(z)

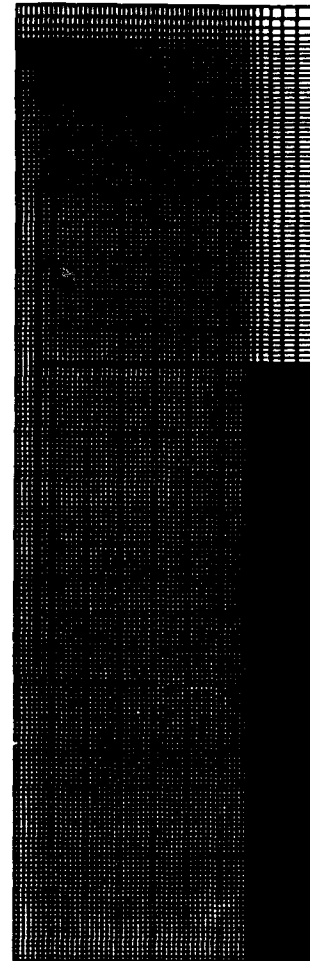


Figure 6. Computational grid for simulating the Task Order 4 tests.



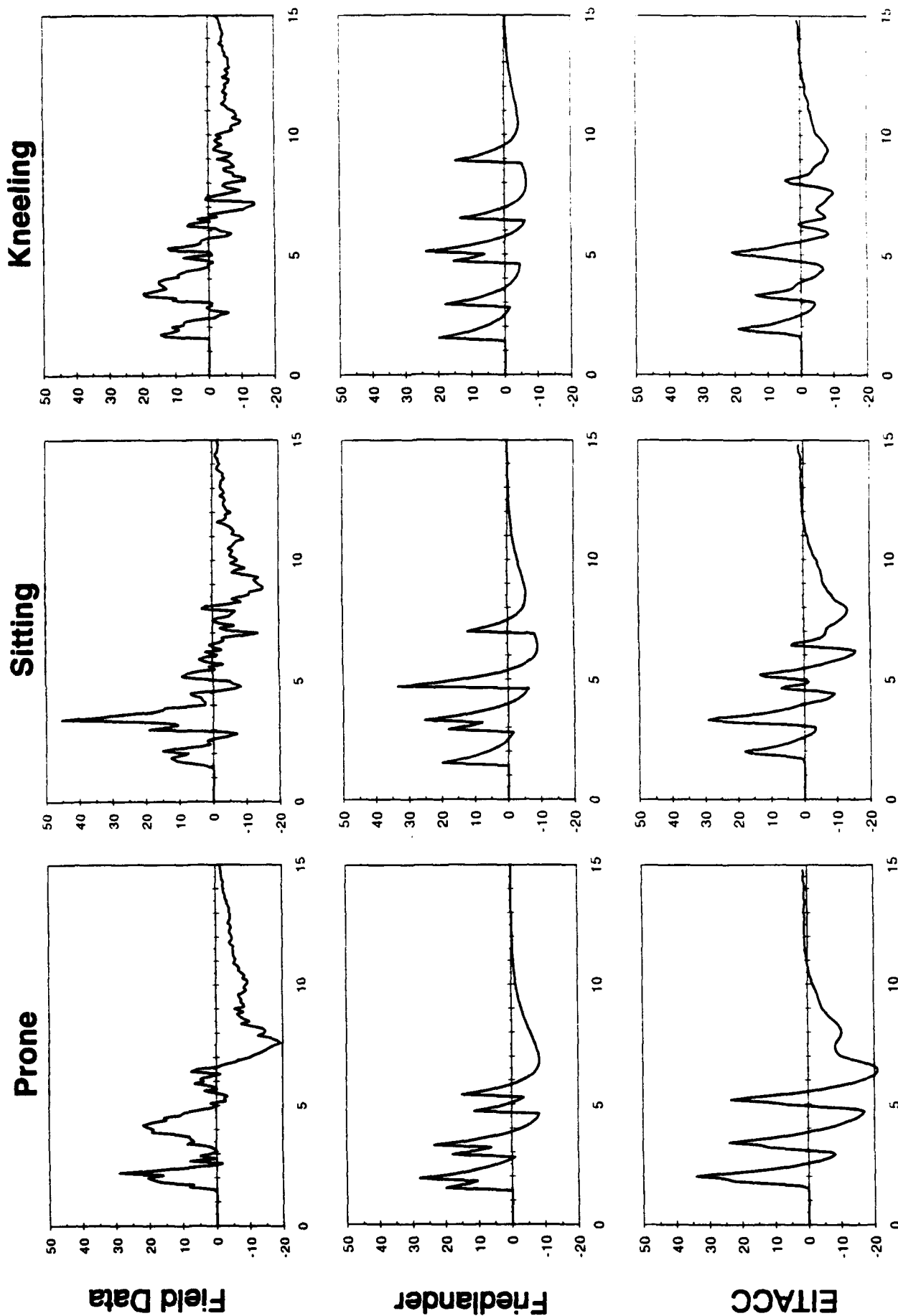


Figure 8. Pressure data for RAAWS weapon taken at gunner's chest compared with superimposed Friedlander waves and with EITACC simulations.

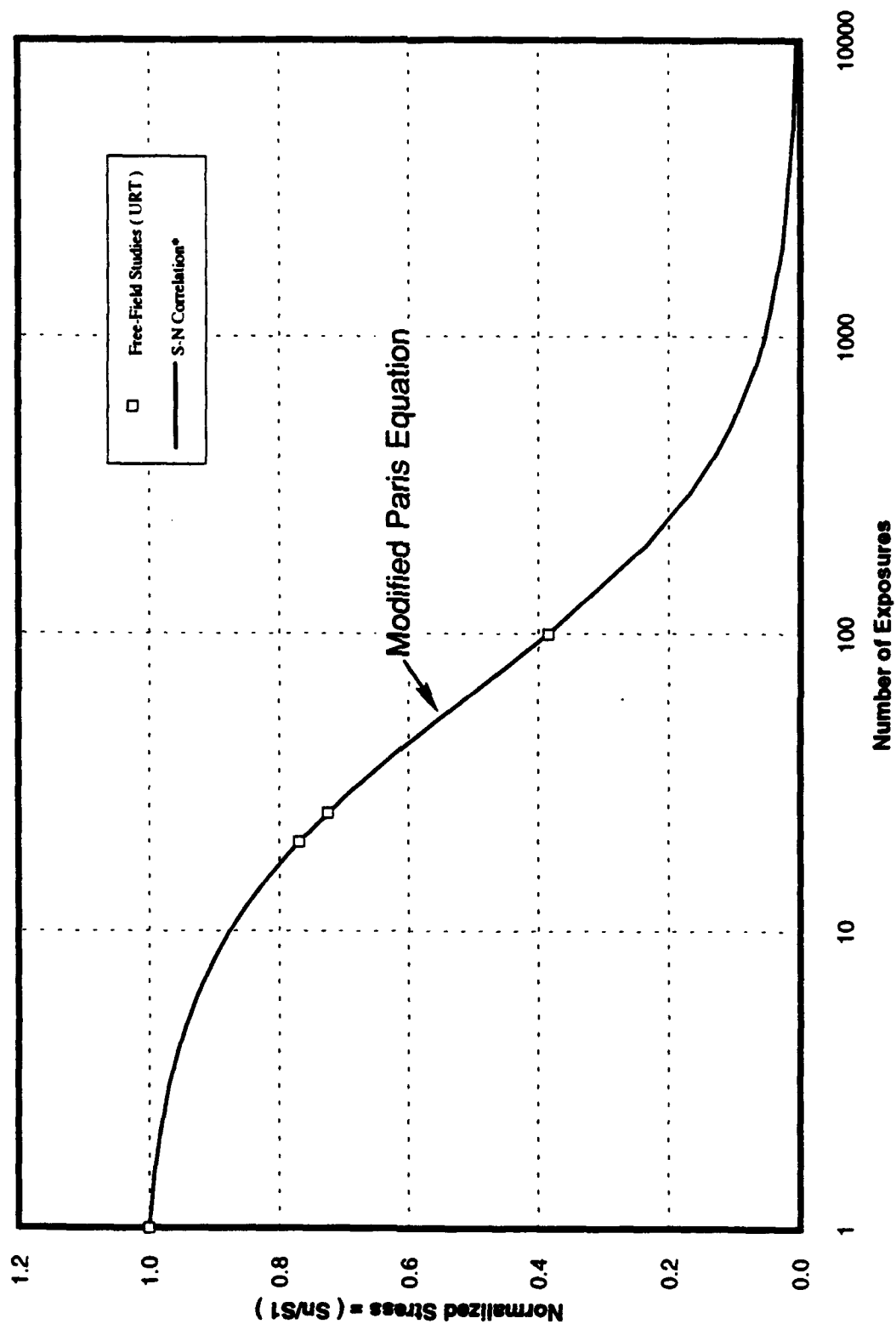


Figure 9. Correlation of injury from repeated exposure with material fatigue.

\* S-N Correlation :  $\text{Log}(S_n/S_1) = 1.93928 - 1.059639 \cdot \text{Log}(n + 66.62899)$ .

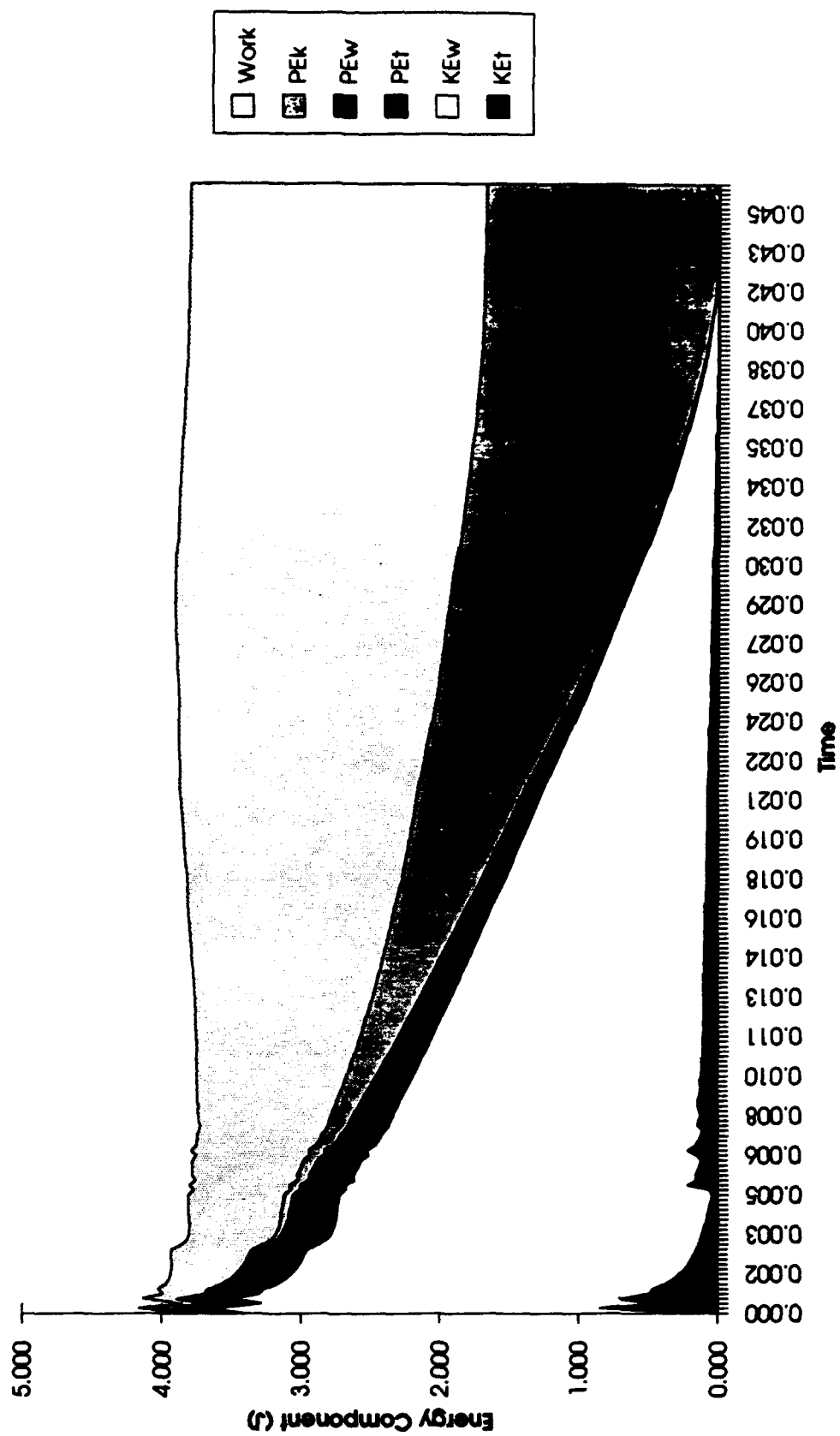
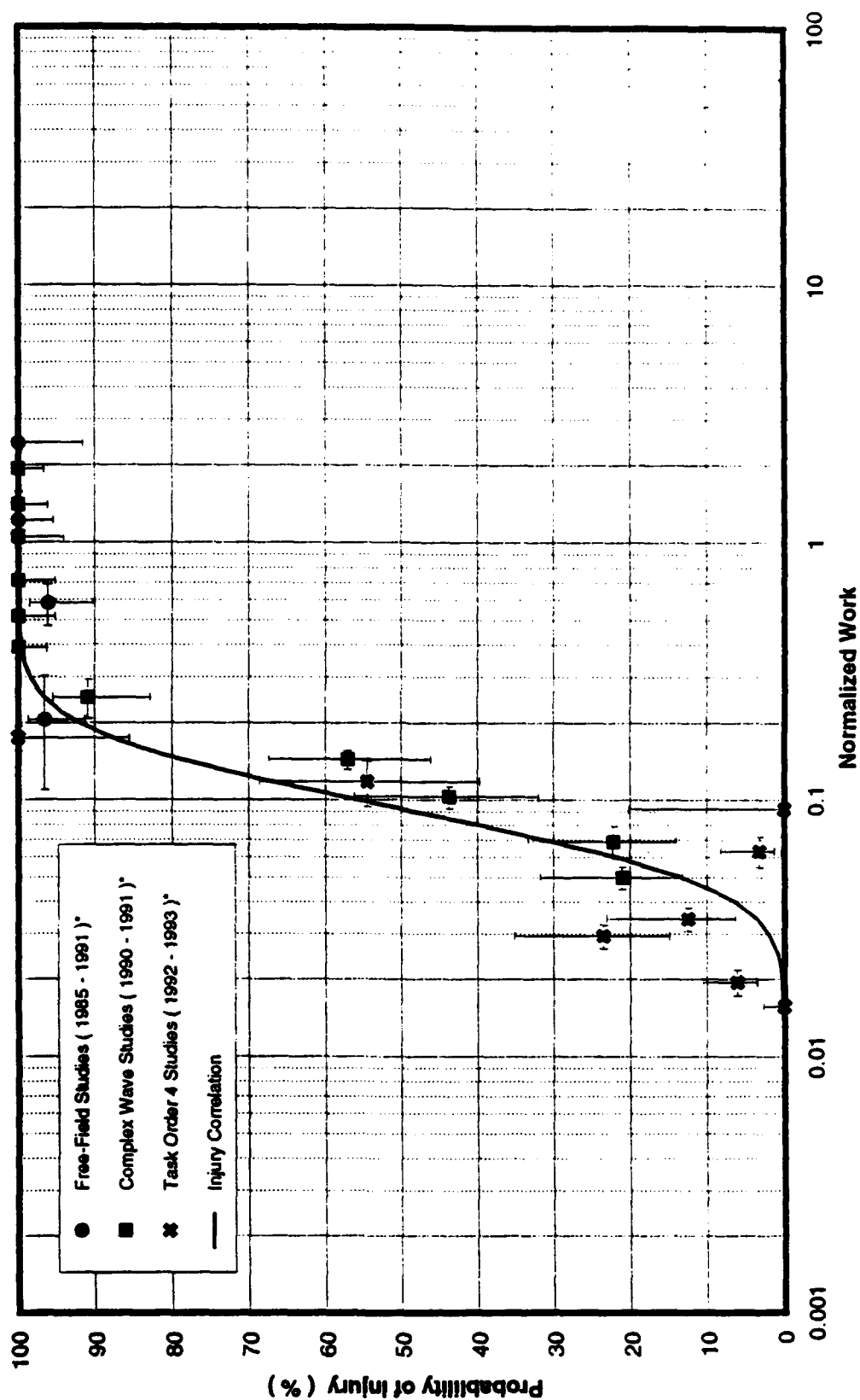


Figure 10. Energy partitioning during impact.

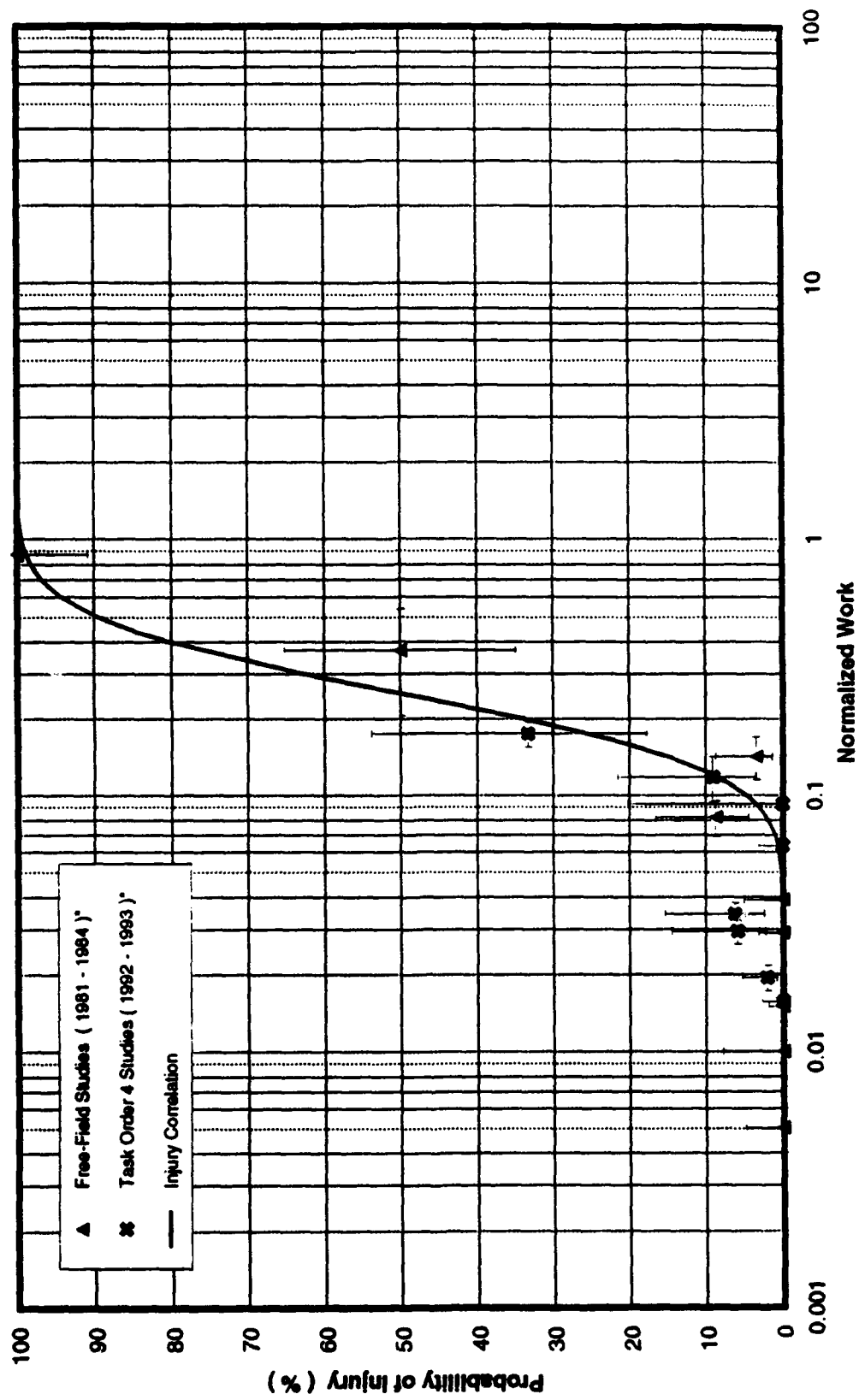
# Lung Injury Correlation



(a)

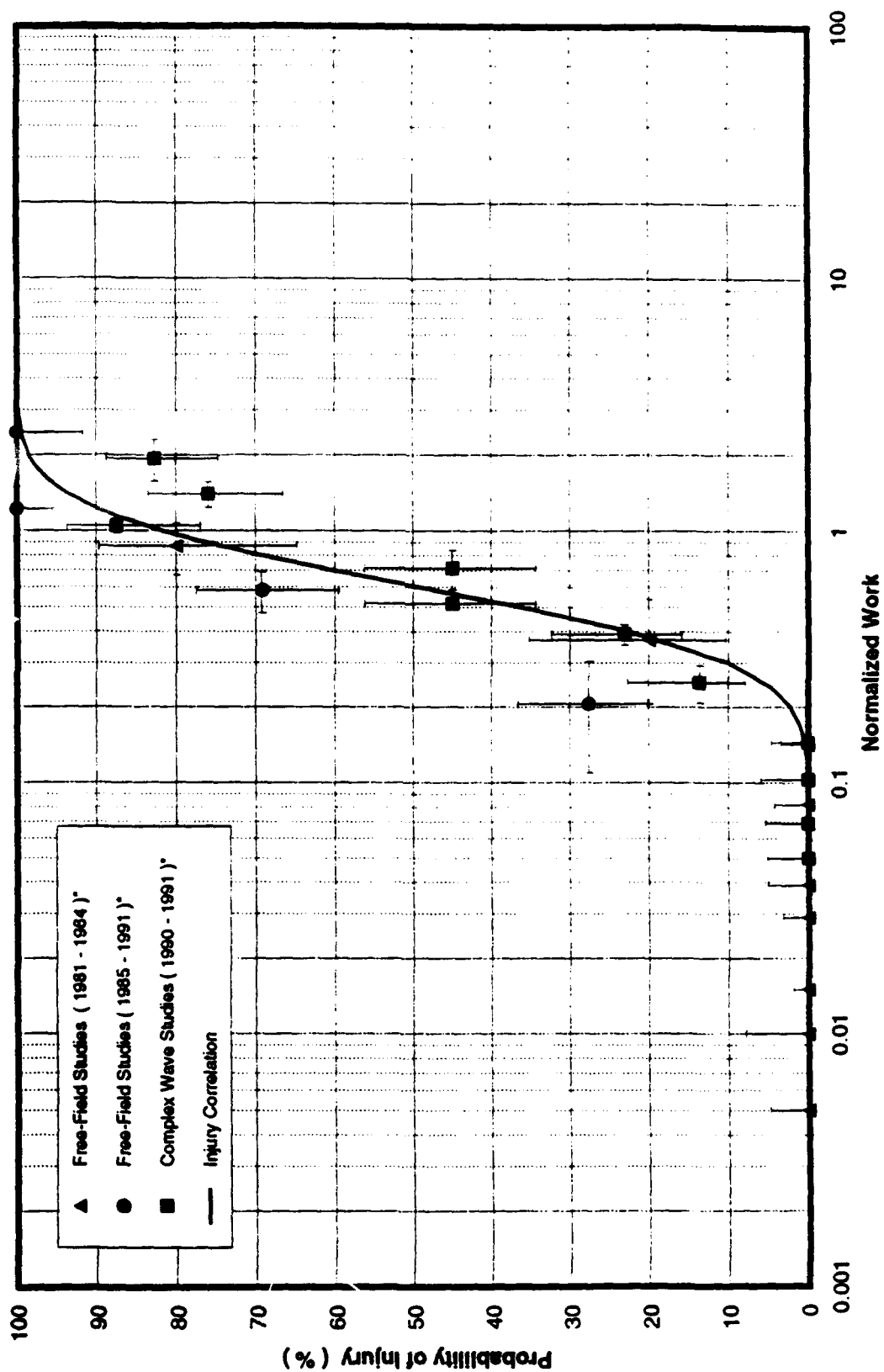
Figure 11. Correlation of normalized work to the lung due to blast loading with observed pathology.

# Lung Injury Correlation



(b)  
Figure 11. Cont'd.

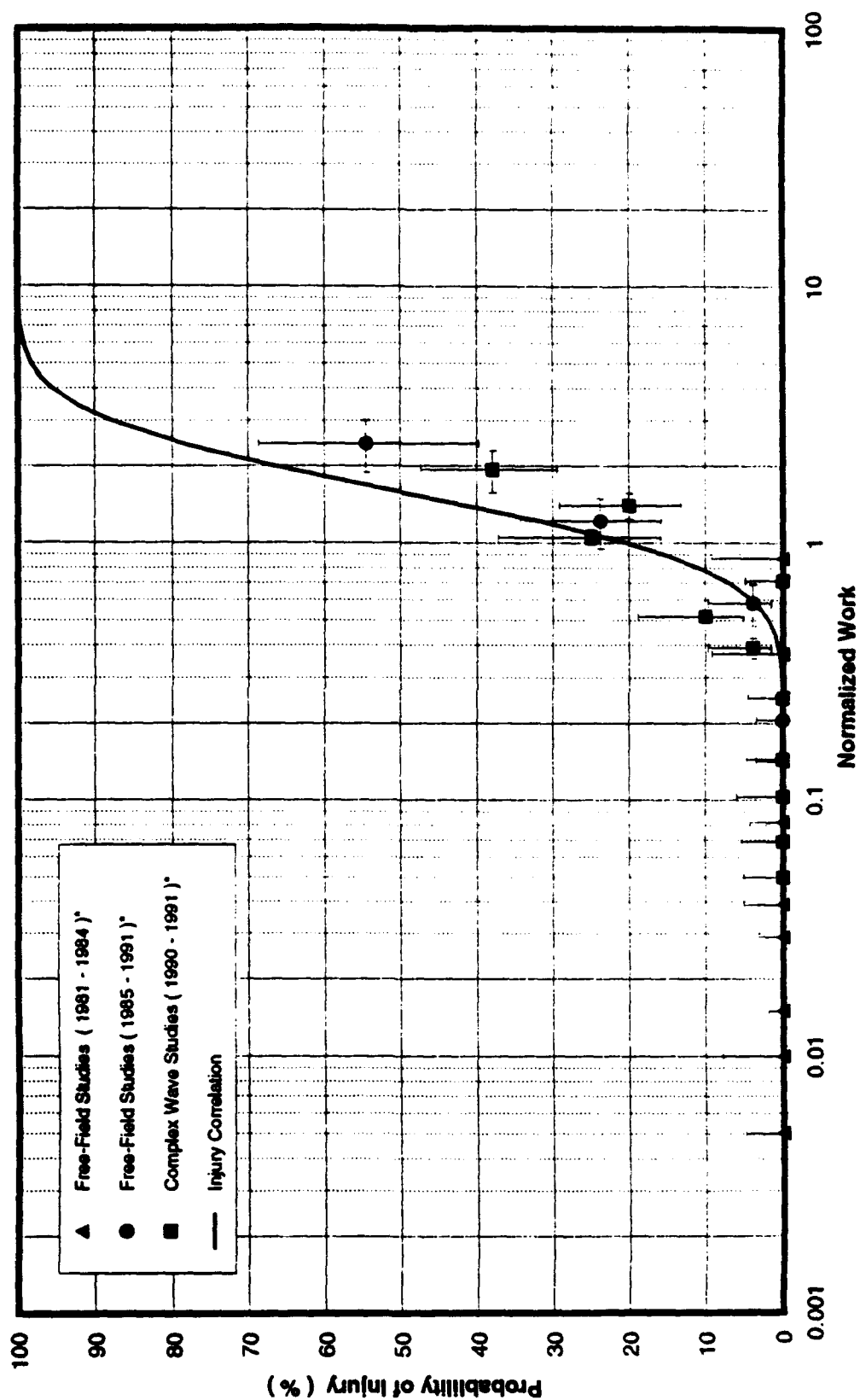
# Lung Injury Correlation



(c)

Figure 11. Cont'd.

# Lung Injury Correlation



(d)

Figure 11. Cont'd.

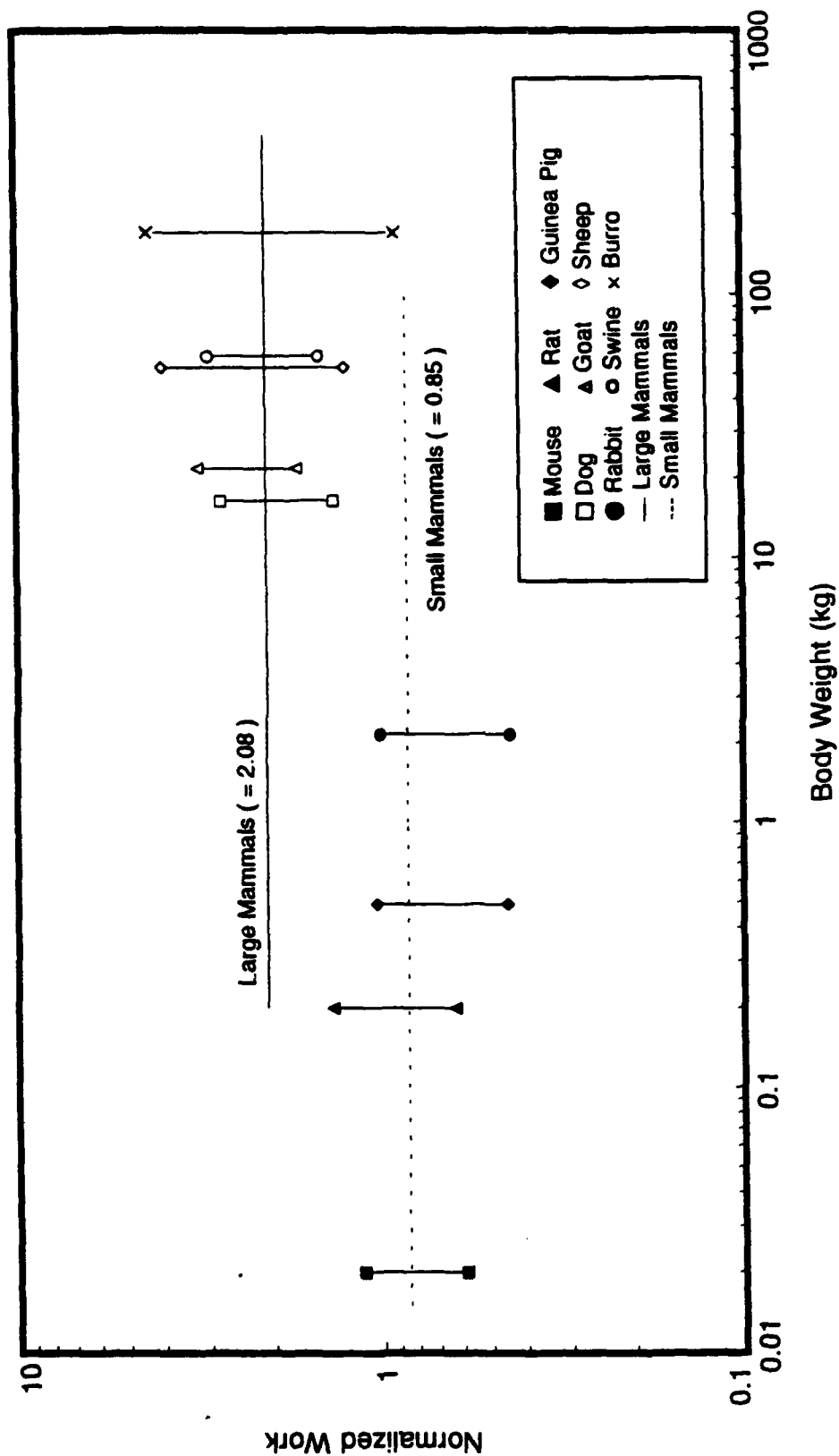


Figure 12. Correlation of normalized work with observed lethality for all species.

## Effect of Pressure Wave of 50 % Mortality of Large Mammals

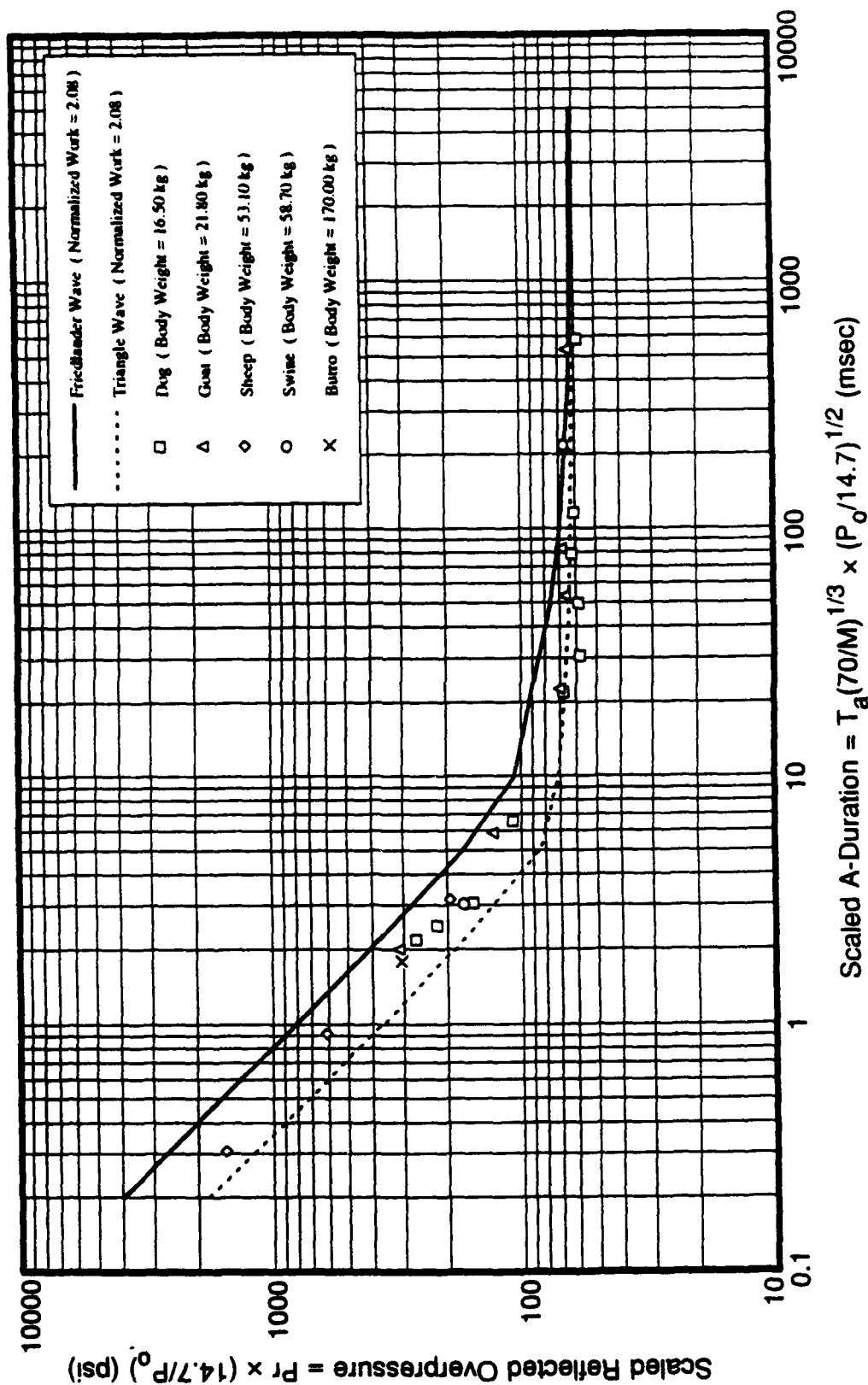


Figure 13. Correlation of normalized work to the lung due to blast loading with observed lethality.